



M³ Overview and Working with M³ Data

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M³ Team

M³ Data Tutorial at EPSC

October, 2011





Topics to be discussed

- Instrument overview
- M³ observation history
- Dataset description
- Calibration pipeline
- Dataset and U2 calibration issues
- Converting radiance to I/F with ENVI





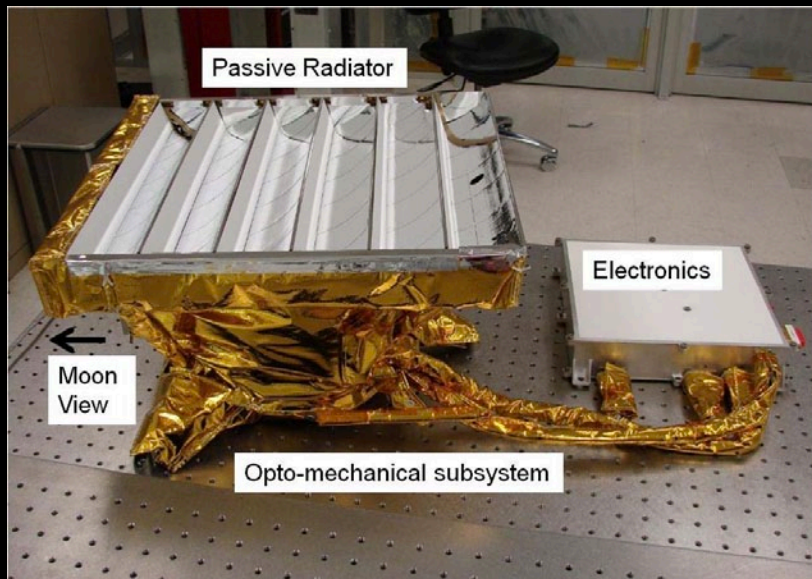
For Reference

- Slides and example data from this workshop available at:
<http://m3.jpl.nasa.gov/m3data.html>
- References for more complete description of these topics:
 - Green et al. (JGR, 2011)
 - Boardman et al. (JGR, 2011)
 - Clark et al. (JGR, 2011)
 - M³ JGR Special Issue:
http://www.agu.org/journals/jg/special_sections.shtml?collectionCode=MOONMMI1





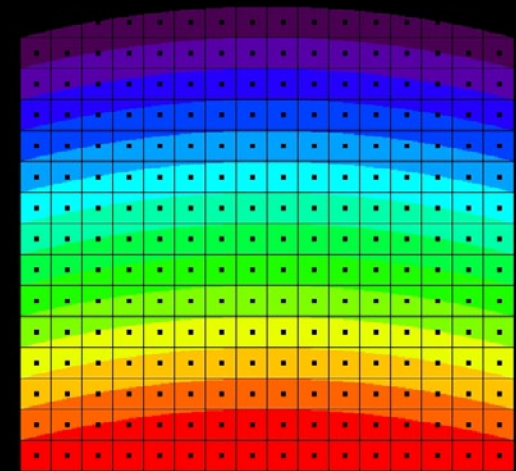
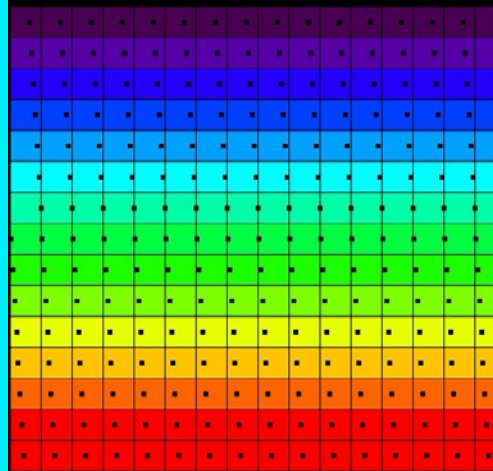
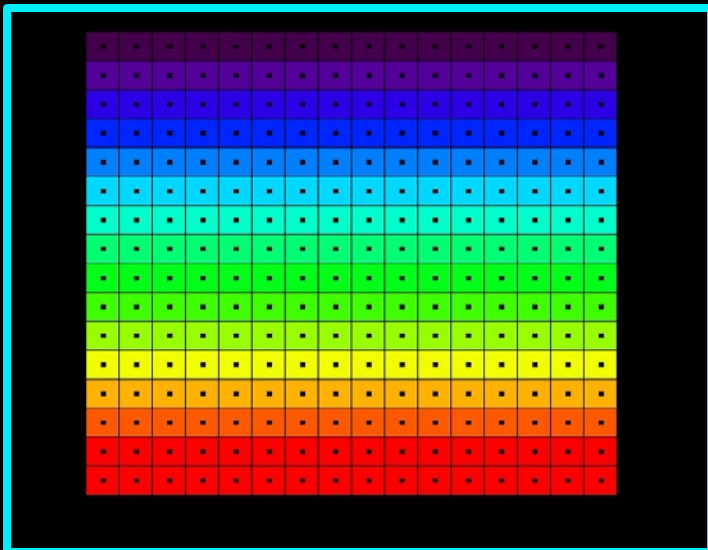
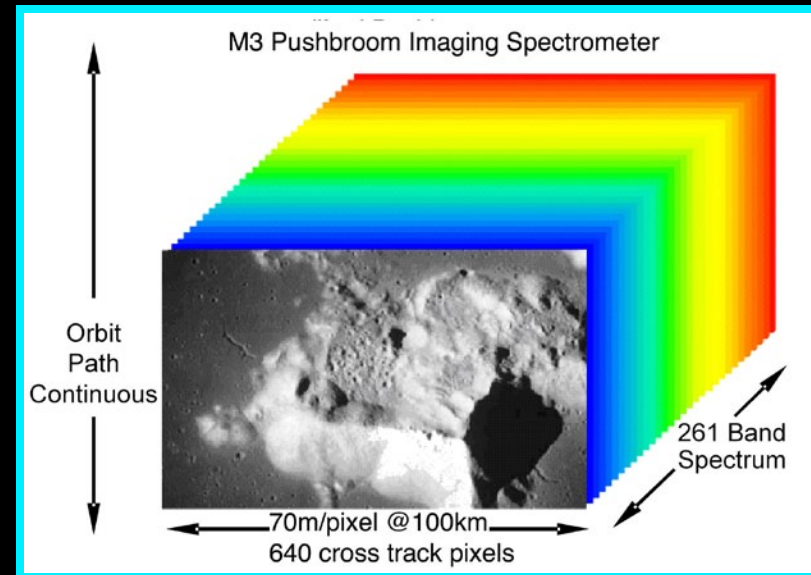
M³ Instrument





Instrument Design

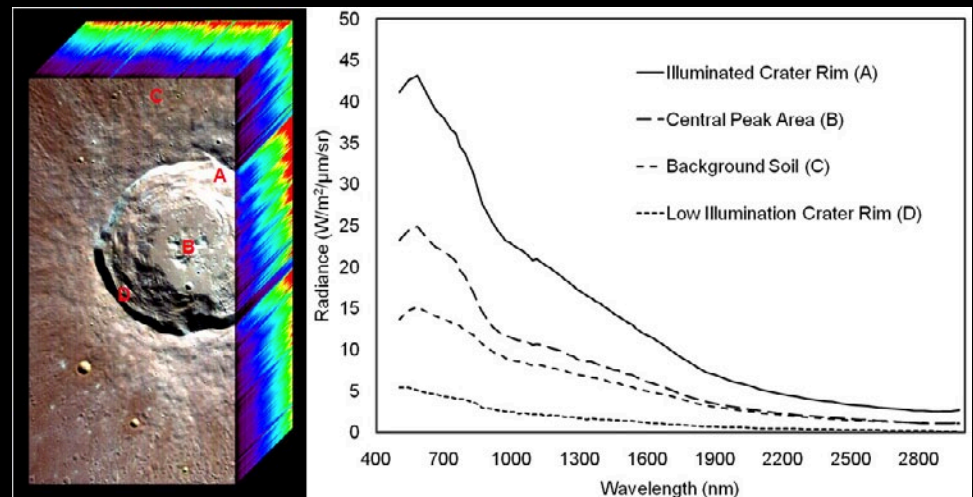
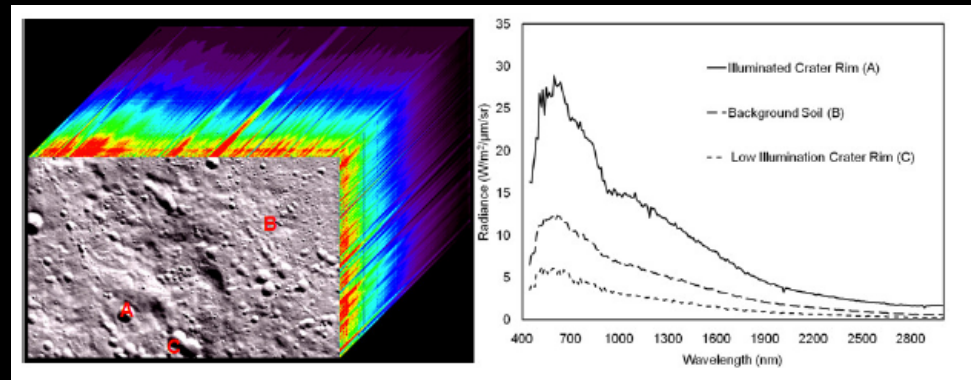
- Pushbroom imaging spectrometer
 - Each detector readout is 1 line of an image cube. The entire image is built as M3 moves along the ground track.
- High Spectral/Spatial Uniformity (>90% spectral crosstrack and spectral IFOV uniformity)





Operational Modes

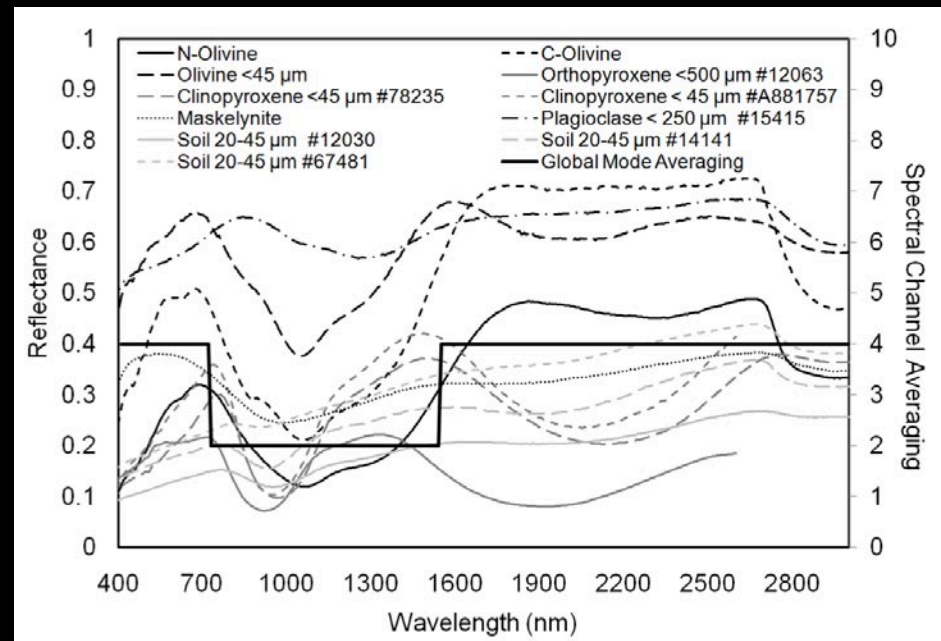
- Target
 - High spatial/spectral resolution mode for priority observations
 - Only a few target observations were actually acquired
- Global
 - M³ instrument acquires full resolution data then onboard software averages data to produce reduced resolution data
 - Lower resolution (spatial & spectral) mode for mapping the entire Moon
 - Majority of the M3 data set is global data





Spatial and Spectral Resolution

- Spectral Coverage:
 - Target: 446-3000 nm
- Spectral Resolution:
 - Target: 10nm
 - Global: 20 or 40 nm
- Spatial Resolution:
 - Target: 70 m/pixel
 - Global: 140 m/pixel
 - Doubled when from 200km orbit (see later discussion of operational history)





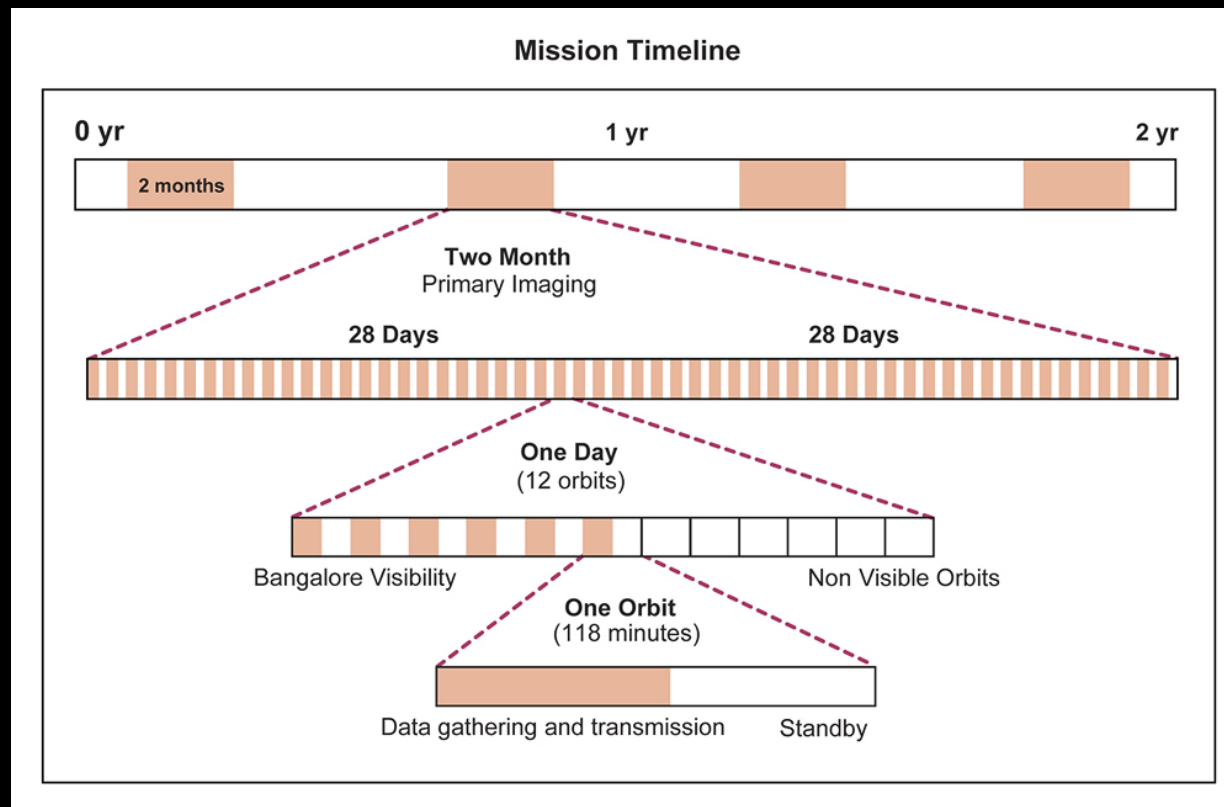
M3 Mission History





Planned vs. Actual Flight

- Planned observation time was 4 two-month optical periods defined by equatorial solar zenith of $\pm 0-30^\circ$





Planned vs. Actual Flight

- Thermal issues plagued the spacecraft as soon as it arrived at the Moon on November 8, 2008
- Lost the 1st of 2 star trackers before a single image was taken
- Extended commissioning phase was required, lasting into Jan 2009





Planned vs. Actual Flight

- The Chandrayaan-1 Mission Operations team did a fantastic job redesigning the mission in real time throughout the mission lifetime
- Despite all the challenges, we were able to meet baseline mission requirements thanks to heroic efforts on the part of Ch-1 and M3 team members
- LOLA topography data were essential for orthorectification (early LOLA grids used)





Planned vs. Actual Flight

- Impact on data:
 - Instrument was operated at less favorable viewing conditions, resulting in lower reflected surface signal and increased effects of shadows.
 - The adverse changing conditions experienced in lunar orbit were beyond the range of ground calibrations for ~80% of M³ data.
 - The spacecraft acquired data intermittently during two optical periods
 - Almost all M3 data were acquired in reduced resolution (“Global”) mode; very few optimal resolution (“Target”) mode observations acquired.
 - Most of 2nd optical period taken at higher orbit (200km vs 100km) and *with no star trackers*.



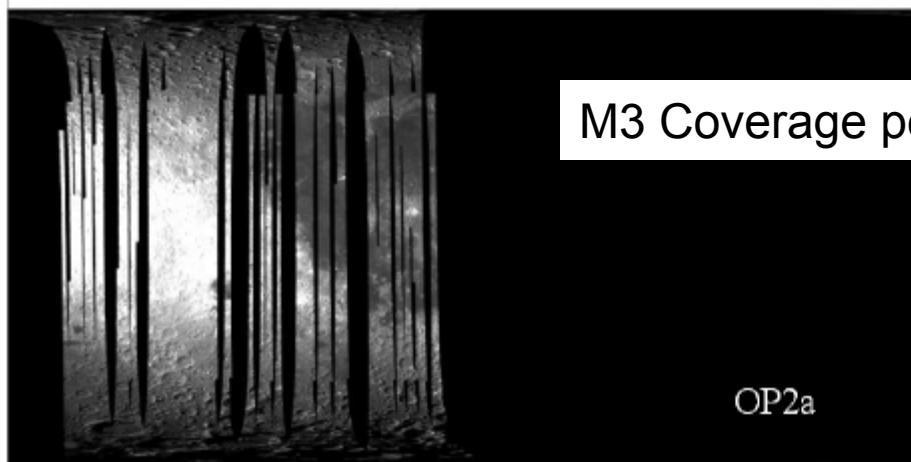
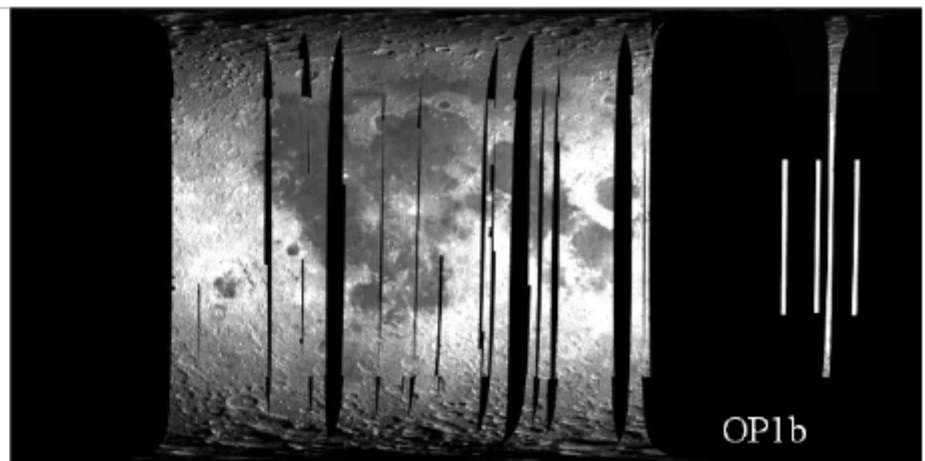
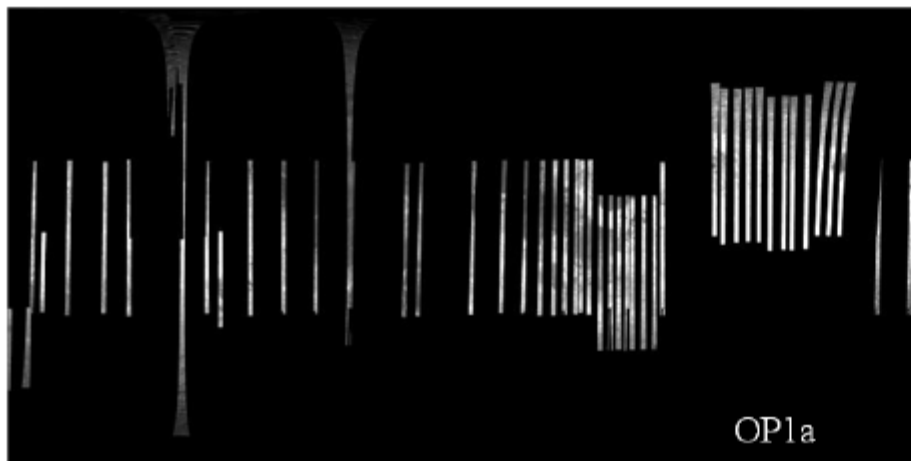


M3 Optical Periods

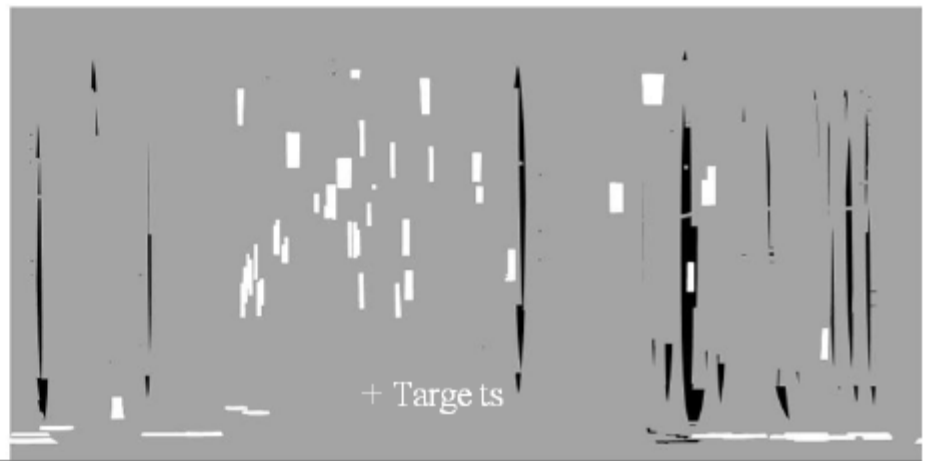
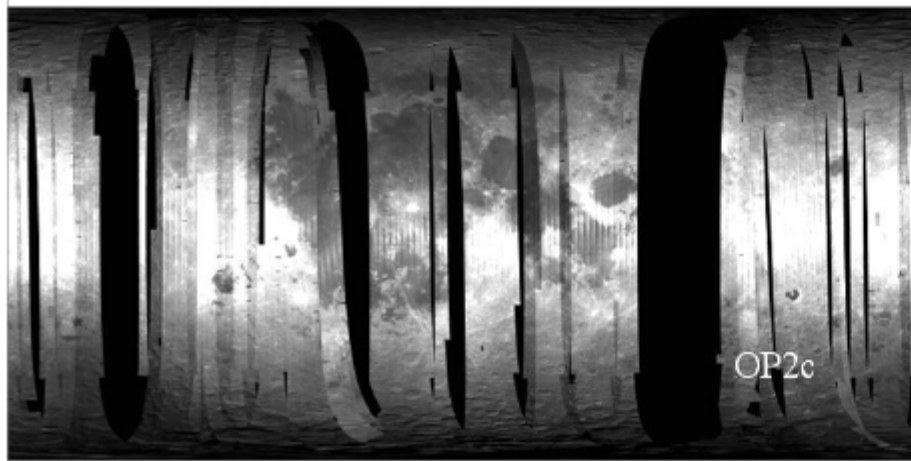
- M3 observed data during two optical periods, defined by favorable viewing conditions
- The team subdivided the optical periods based on data characteristics:

<u>Period</u>	<u>Dates</u>	<u>Images</u>	<u>Orbit</u>	<u>Sensors</u>	<u>Star</u> <u>Status</u>
OP1A	Nov 18 - Jan 24	119	100 km	1 of 2	extended commissioning
OP1B	Jan 25 - Feb 14	247	100 km	1 of 2	operational, high solar zenith angles
OP2A	Apr 15 - Apr 27	197	100 km	1 of 2	operational, high solar zenith angles
OP2B	May 13 - May 16	20	200 km	0 of 2	S/C emergency, orbit raised
OP2C	May 20 - Aug 16	375	200 km	0 of 2	operational, variable conditions



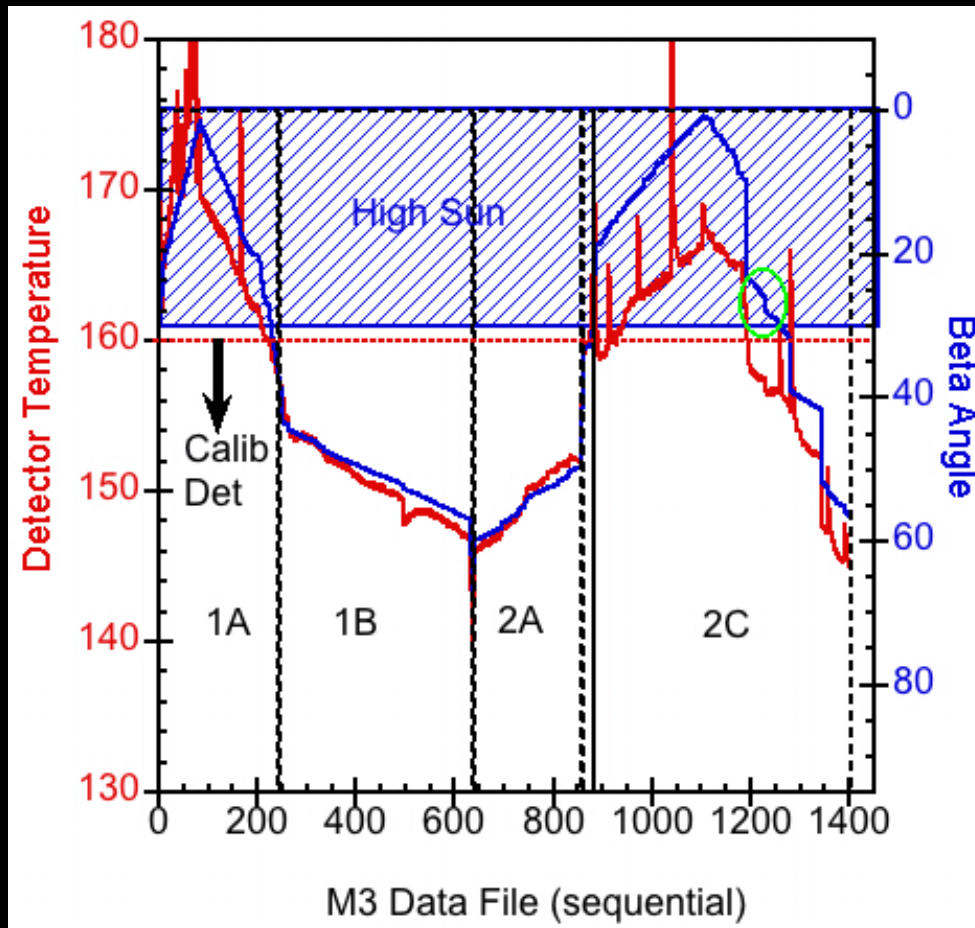


M3 Coverage per OP + Targets





M3 Optical Periods



- High detector temperatures were encountered when observations were made at optimal high sun conditions. Very low detector temperatures were only encountered during periods of very low sun angle



PDS Releases

- Level 0 and Level 1B:
 - OP1 (R3, R4 calibration): June 2010
 - OP2 (R4 calibration): December 2010
 - *OP1 and OP2 (U2 calibration): delivered to PDS 9/30/11*
- Level 2 (projected U2 calibration):
 - OP1 and OP2: Late 2011

L0 = raw spacecraft data, L1b=radiance + backplanes, L2 = reflectance





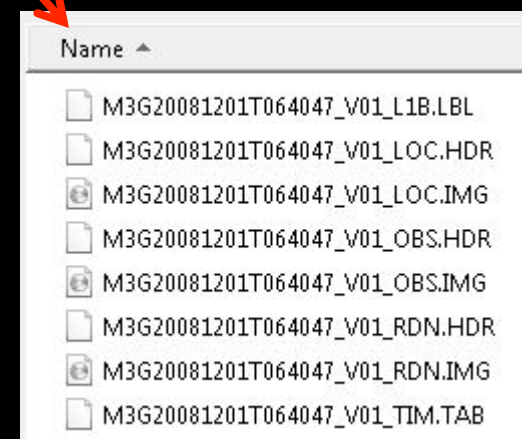
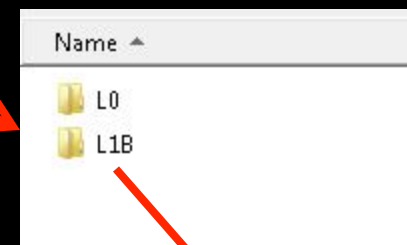
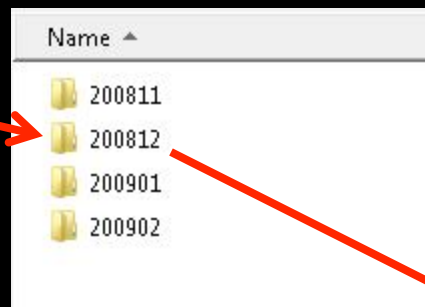
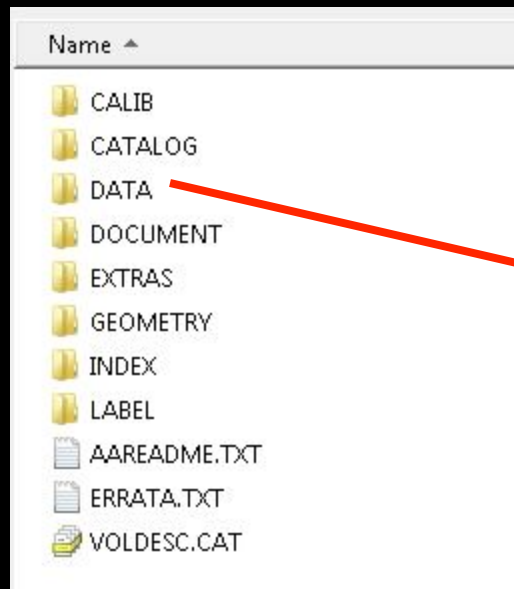
M3 File Formats/PDS Structure





PDS Directory Structure

- Standard PDS structure





M3 File Naming Convention

M3G20090204T113444_V01_RDN.IMG

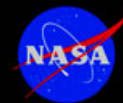
Basename

Pipeline

Data
Type

File
Type

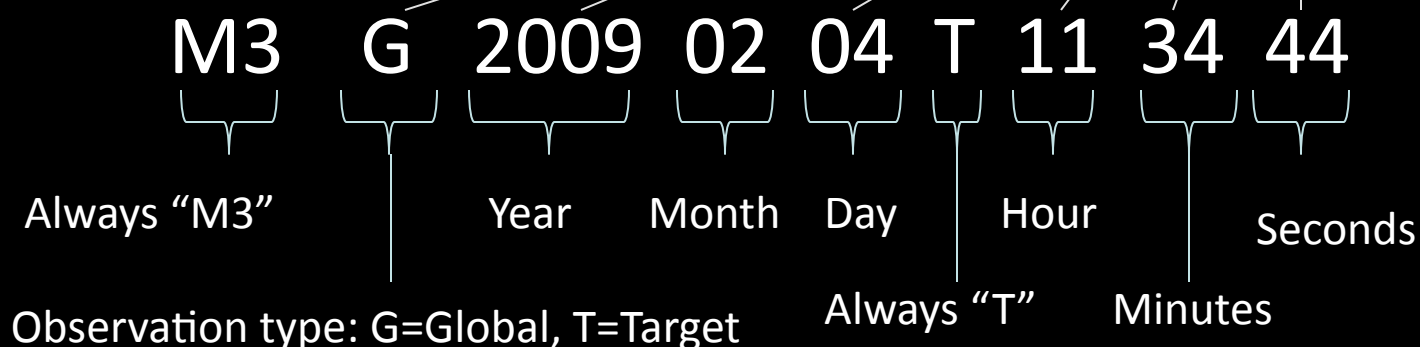
- Basename – covered next slide
- Pipeline – not used: was to be pipeline run number, but is always “V01” in PDS data
- Data type – tells you the type of information stored in the file
 - Possible values in L1B delivery:
 - LO – raw spacecraft data
 - RDN – radiance
 - OBS – observational data (incidence, emission, phase angles, etc.)
 - LOC – location data (latitude, longitude, radius)
 - TIM – time of observation
- File Type – tells you the file format
 - Possible Values in L1B delivery:
 - IMG – raw binary image data
 - HDR – ENVI header
 - LBL – PDS label
 - TAB – tabular data stored in ASCII format





M3 File Naming Convention (cont'd)

Example Basename: M3G20090204T113444



Note: Sorting by filename is only equivalent to sorting by observation time if you do not have global and target data mixed together. If you do have a mix of the two, remove the first three characters then sort by filename to also sort by observation time.





M3 image data format

- The following applies to all M3 image data:
- Files are raw binary data (no offset)
- Interleave is BIL (line-interleaved)
- Global data have 304 samples (columns) for all image types (except L0, which has 320)
- Targeted data have 608 samples (L0 has 640)
- Number of lines (rows) is variable (determined by length of observation)
- Data type is 32-bit floating point (LOC files are 64-bit double precision floating point)
- “Backplanes” = OBS, LOC, and TIM files



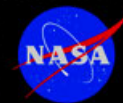


M3 Data types: L0

M3G20090126T033545_V01_L0.IMG



- L0 is raw spacecraft data, units are DN
- 320 samples which are reduced to 304 when converted to radiance
 - The 16 columns that are removed are for monitoring dark signal level and scattered light
- Each frame has a 1280-byte header
- To directly compare L0 to radiance:
 - No sample or line flip starting Nov 16 2008
 - Sample only flip starting Dec 18 2008
 - Line only flip starting Mar 14 2009
 - Sample and line flip starting Jun 18 2009



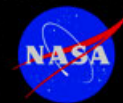


M3 Data Types: L1B RDN

M3G20090126T033545_V01_RDN.IMG



- Radiance data, units $W/(m^2 \text{ Sr } \mu m)$
- Steps used to create radiance described in calibration slides
- PDS label or ENVI header can be used to open files
- ENVI Header contains:
 - Calibration steps
 - Target wavelengths (averaging for global)
 - Target FWHM
 - Dark Signal Image
 - Anomalous Detector Map
 - Flat Field Image
 - Detector Temperature
 - Beta Angle
 - Sample/Line flip code





M3 Data Types: OBS

- List of bands in OBS file:
 - To-Sun Azimuth (deg)
 - To-Sun Zenith (deg)
 - To-M3 Azimuth (deg)
 - To-M3 Zenith (deg)
 - Phase (deg)
 - To-Sun Path Length (au-0.981919816030)
 - To-M3 Path Length (m)
 - Facet Slope (deg)
 - Facet Aspect (deg)
 - Facet Cos(i) (unitless)
- Values in the To-Sun Path Length band are the difference from the scene mean path length.

Scene-mean
to-Sun path
length



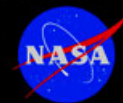


M3 Data Types: OBS

Phase angle band



Facet cos(i) angle band





M3 Data Types: LOC

- List of channels in LOC file:
 - Longitude
 - Latitude
 - Radius
- Subtract lunar radius of 1737400 m to get difference in elevation from reference sphere
- Based on LOLA topography (see Boardman et al., in press)
- Reference frame is Moon Mean Earth Polar Axes (MOON_ME) frame



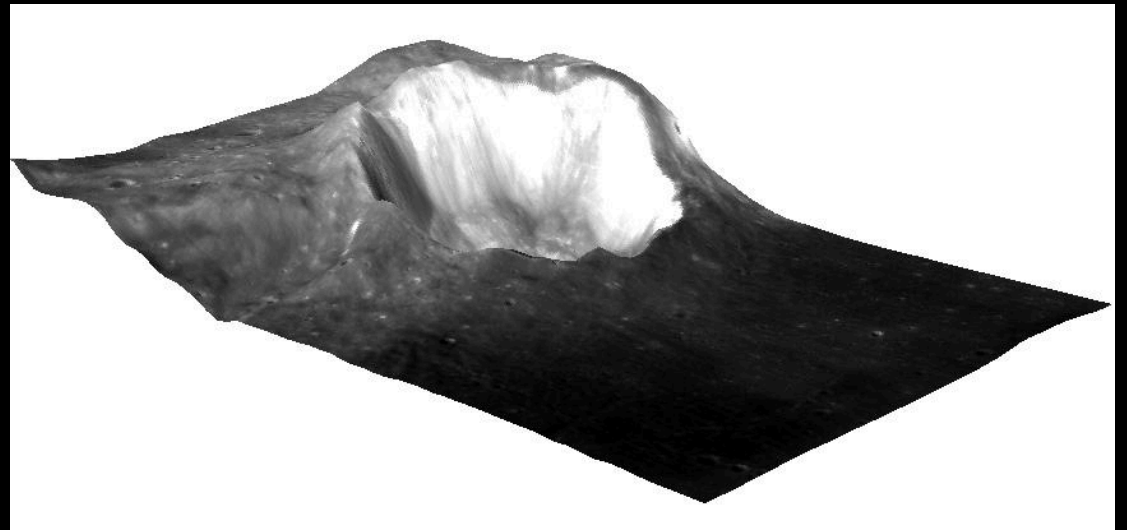


M3 Data Types: OBS

Band 3 “Radius”



750 nm albedo draped over “Radius” band





M3 Data Types: TIM

One ASCII text record per frame:

Column 1:
Frame Number

Column 2: UTC Time

Column 3:
Year

Column 4:
Decimal
Day of Year

Frame Number	UTC Time	Year	Decimal Day of Year
1	2008-11-18T22:26:03.491014	2008	322.934762614844
2	2008-11-18T22:26:03.592772	2008	322.934763792605
3	2008-11-18T22:26:03.694531	2008	322.934764970366
4	2008-11-18T22:26:03.796289	2008	322.934766148128
5	2008-11-18T22:26:03.898048	2008	322.934767325889
6	2008-11-18T22:26:03.999806	2008	322.934768503650
7	2008-11-18T22:26:04.101565	2008	322.934769681411
8	2008-11-18T22:26:04.203324	2008	322.934770859173
9	2008-11-18T22:26:04.305082	2008	322.934772036933
10	2008-11-18T22:26:04.406841	2008	322.934773214695
11	2008-11-18T22:26:04.508599	2008	322.934774392456
12	2008-11-18T22:26:04.610358	2008	322.934775570217
13	2008-11-18T22:26:04.712116	2008	322.934776747979
14	2008-11-18T22:26:04.813875	2008	322.934777925740
15	2008-11-18T22:26:04.915634	2008	322.934779103501
16	2008-11-18T22:26:05.017392	2008	322.934780281262
17	2008-11-18T22:26:05.119151	2008	322.934781459024
18	2008-11-18T22:26:05.220909	2008	322.934782636785
19	2008-11-18T22:26:05.322668	2008	322.934783814546
20	2008-11-18T22:26:05.424426	2008	322.934784992307
21	2008-11-18T22:26:05.526185	2008	322.934786170069
22	2008-11-18T22:26:05.627944	2008	322.934787347830
23	2008-11-18T22:26:05.729702	2008	322.934788525591
24	2008-11-18T22:26:05.831461	2008	322.934789703352
25	2008-11-18T22:26:05.933219	2008	322.934790881114
26	2008-11-18T22:26:06.034978	2008	322.934792058875
27	2008-11-18T22:26:06.136736	2008	322.934793236636



Good Stuff in the PDS Directories

- CALIB
 - Record of detector temperatures, band pass functions, spectral calib. File (wavelength center positions), radiometric calibration coefficients
- DOCUMENT
 - Data Product SIS document that describes all files released to PDS down to the byte level; Archive Volume SIS describes PDS directory structure
- EXTRAS
 - Flat fields, anomalous detector element maps, quicklooks





Calibration





Converting L0 to L1 (Radiance)

- M3 Global Mode Calibrated Data version r4
- Raw image;
- Dark signal subtraction;
- Anomalous detector element interpolation;
- Interpolate filter edges c13, c50;
- Interpolate detector panel edges s81, s161, s241;
- Electronic panel ghost correction;
- Dark pedestal shift correction;
- Scattered light correction;
- Laboratory flat field;
- Image based flat field w/ photometry preserved;
- Nonlinearity correction
- Apply radiometric calibration coefficients;
- Apply shape correction
- Units ($\text{W/m}^2/\mu\text{m}/\text{sr}$)

See Green et al. (JGR, 2011) and L1B SIS PDS document for more detailed description.





Basic calibration equation

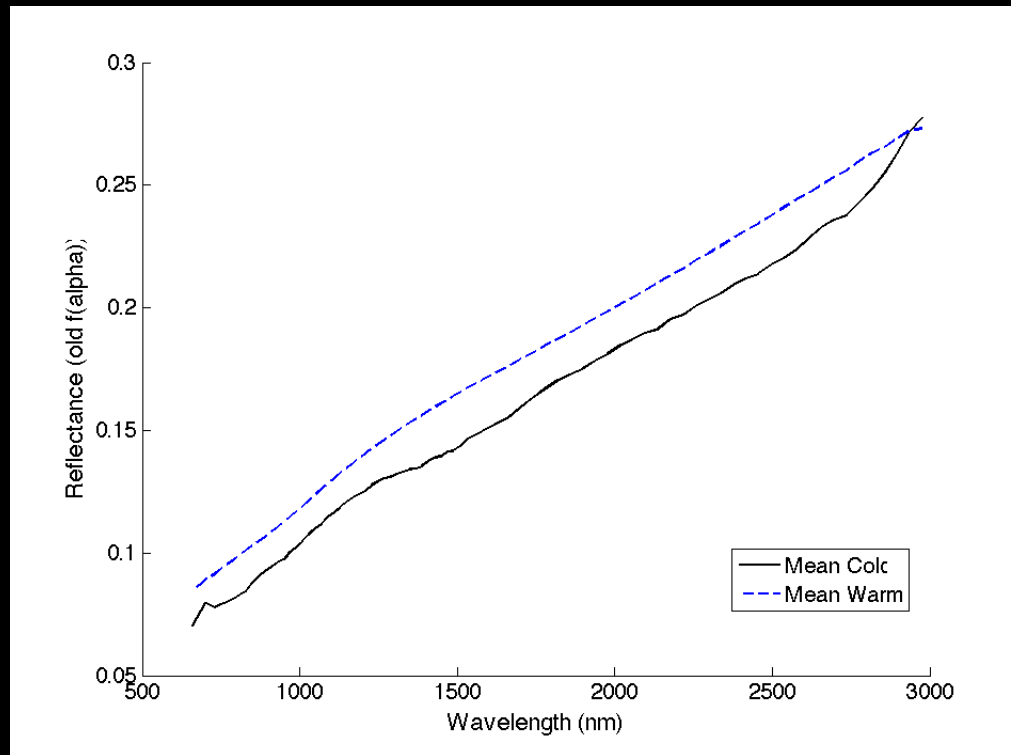
$$L_{l,s,\lambda} = RCC_{\lambda} (C_{s,\lambda} (DN_{l,s,\lambda} - \overline{DS}_{s,\lambda}))$$

- L = calibrated radiance
- RCC = radiometric calibration coefficients
- C = term encompassing all correction factors (flat fields, etc.)
- DN = raw digital number
- DS = dark signal





Shape correction

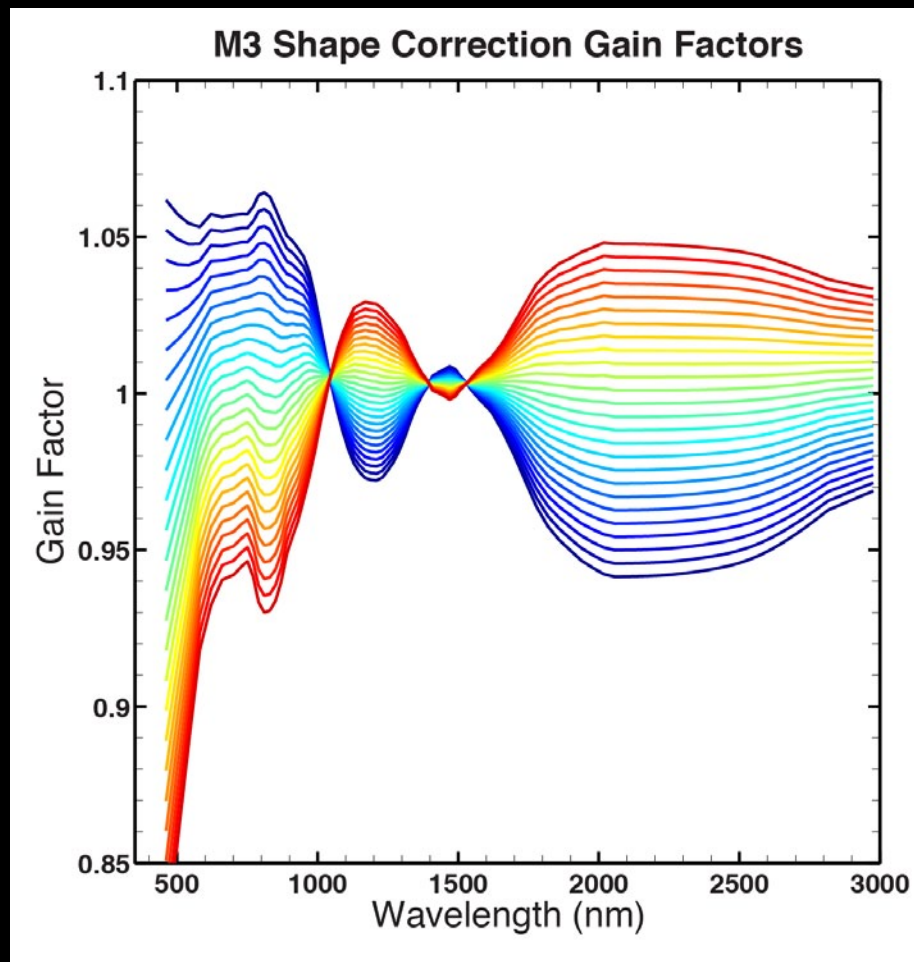


- “Raw signal” artifacts apparent in data collected under variable operational conditions
- Most apparent in ratios of spectra from identical regions but with variable detector temperatures
- Mitigation approach: scene subset covering same region under several detector temperature conditions
- Derive gain factors that force spectral ratios to be flat (ratios over the same terrain should not exhibit spectral variability)





Shape correction



- Interpolate for full detector temperature coverage
- Applied To *delivered* U2 radiance L1B data
- Gain factor used is recorded in label files (reversible correction)
- In EXTRAS directory, individual per image (named with BASENAME_SSCADJ.TAB)





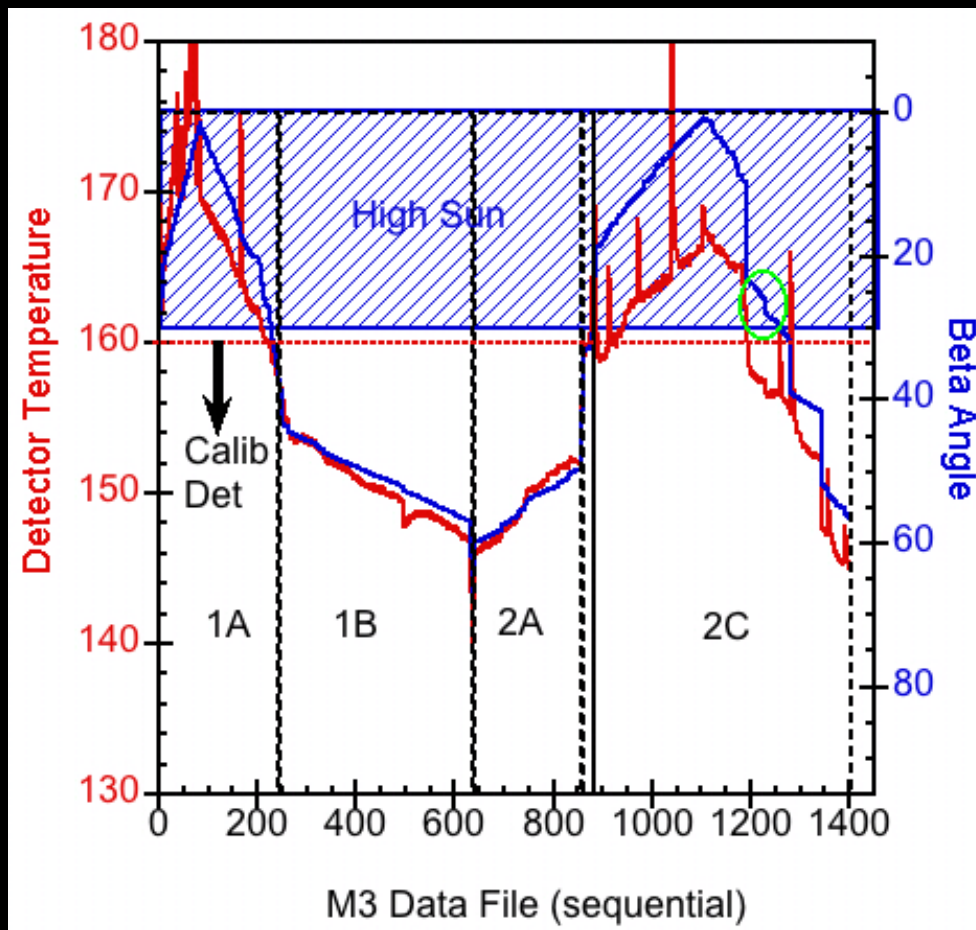
Converting L1 to L2 (Reflectance)

- M3 Global Mode Calibrated Data version u2
- Radiance image
- Divide by solar irradiance
- Statistical polisher
- Remove thermal emission
- Photometric correction
- Ground truth correction
- Units are reflectance (0-1)





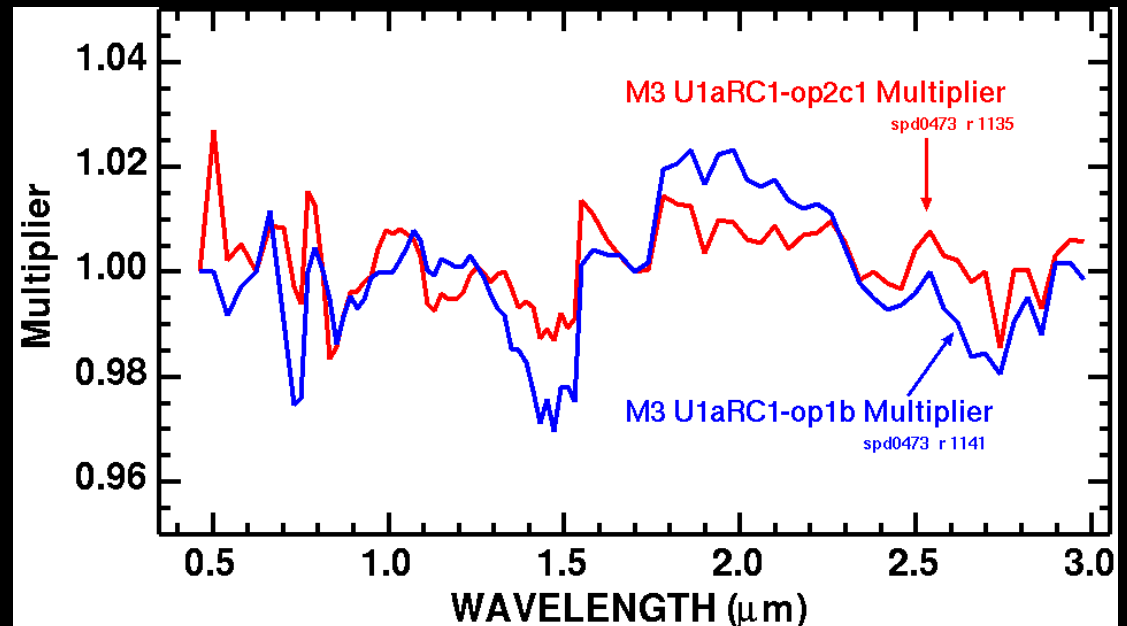
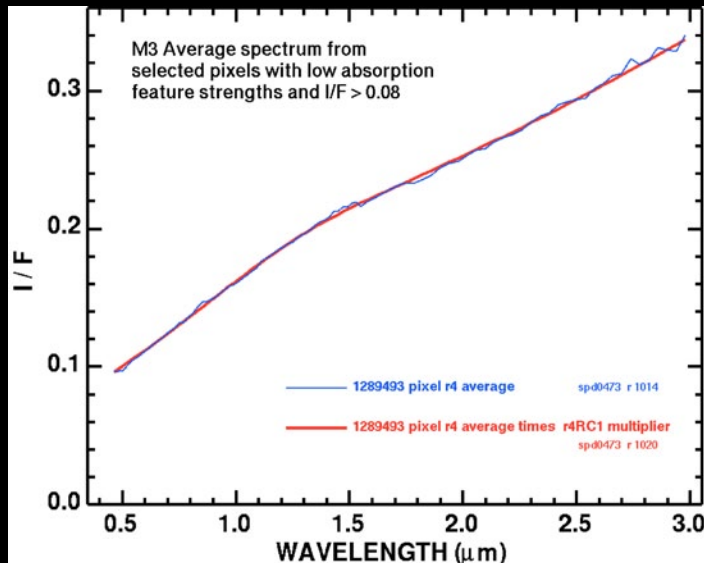
Statistical Polishing



- Goal: remove systematic band-to-band artifacts in M3 data.
- Temperature dependence: strong temperature variations resulting from spacecraft thermal challenges require different “polishers” from different input data “suites”.



Statistical Polishing

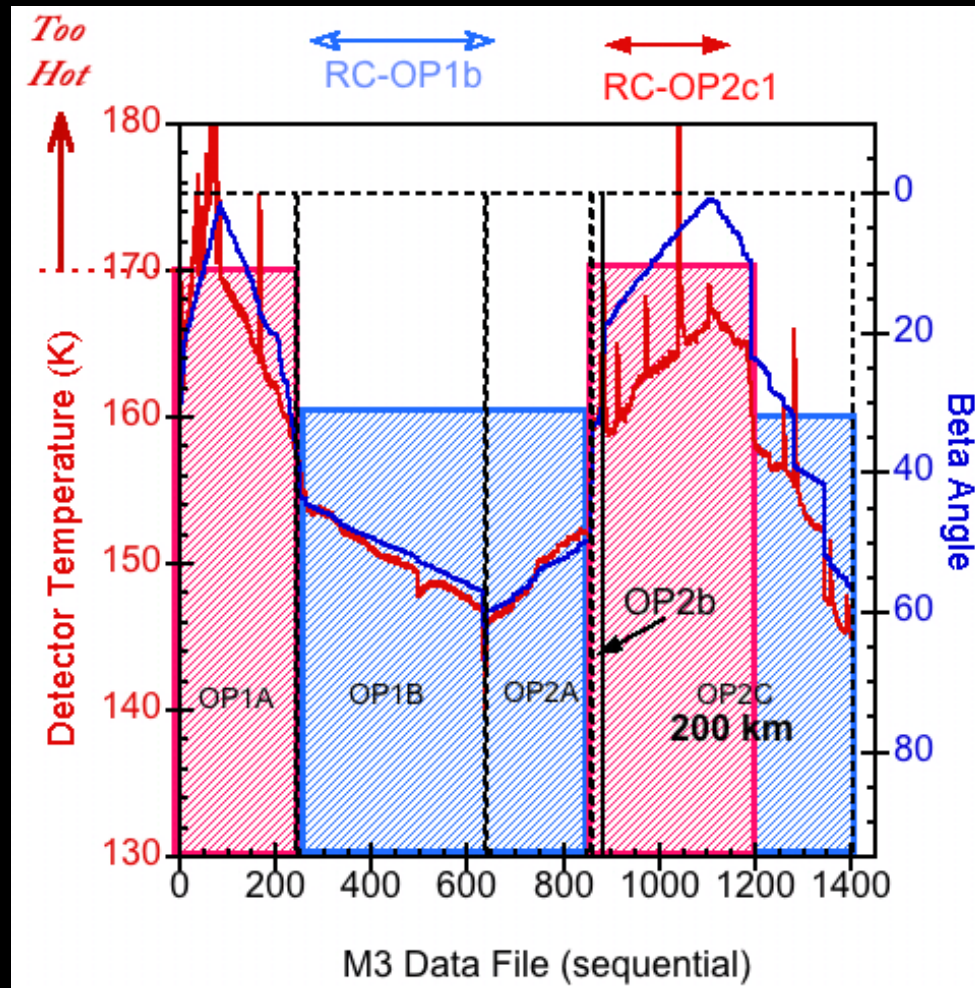


- Select a large suite of “featureless” spectra (A)
- Perform cubic spline fit (manual) to average spectrum (B)
- Polisher = A / B
- Temperature dependence: distinct polishers from distinct input suites
- Gain factors stored in L2 CALIB directory; pointers in label files.





Statistical Polishing: Application



Polisher application summary:

OP1

HOT: 11/18/2008 – 1/18/2009

COLD: 1/19/2009 – 2/14/2009

OP2

COLD: 4/15/2009 – 4/27/2009

HOT: 5/13/2009 – 5/16/2009

-----altitude change-----

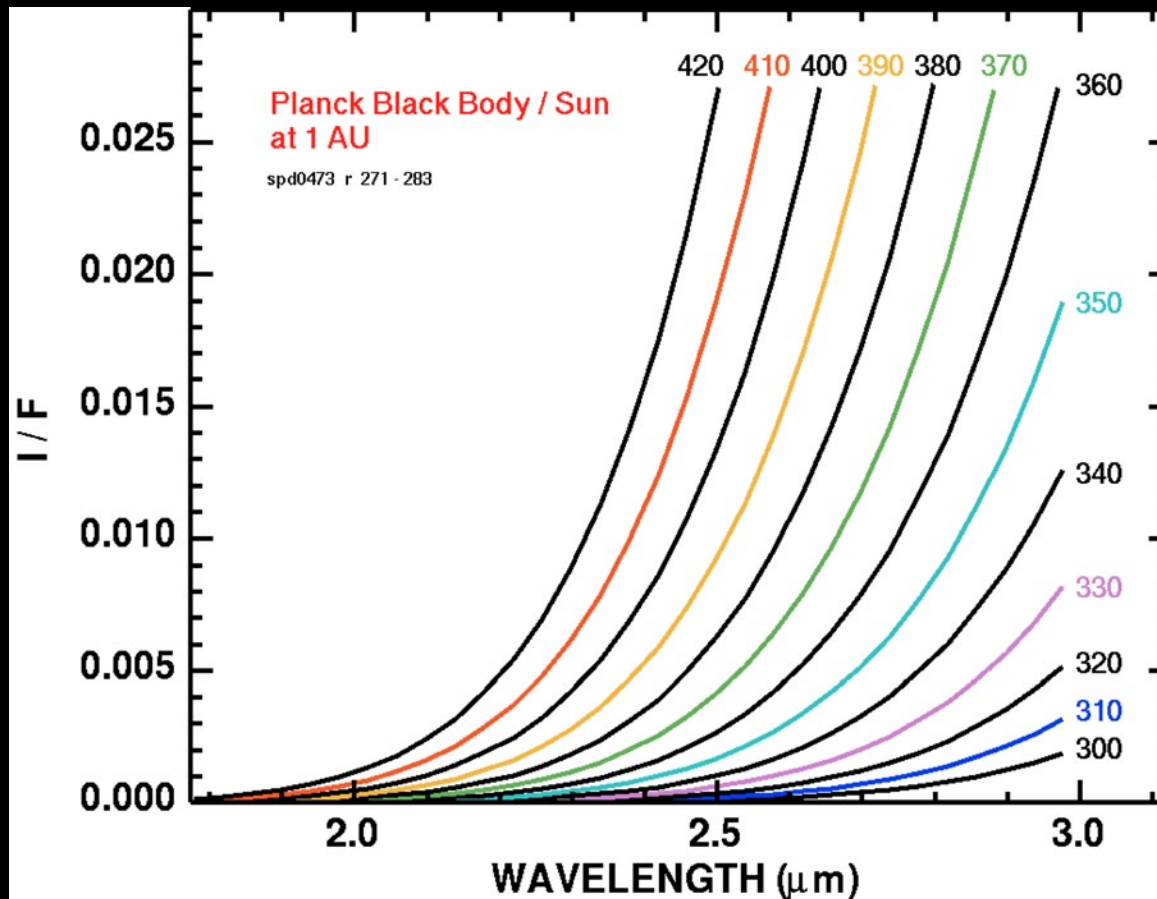
HOT: 5/20/2009 – 6/27/2009

COLD: 7/12/2009 – 8/16/2009





Thermal Removal



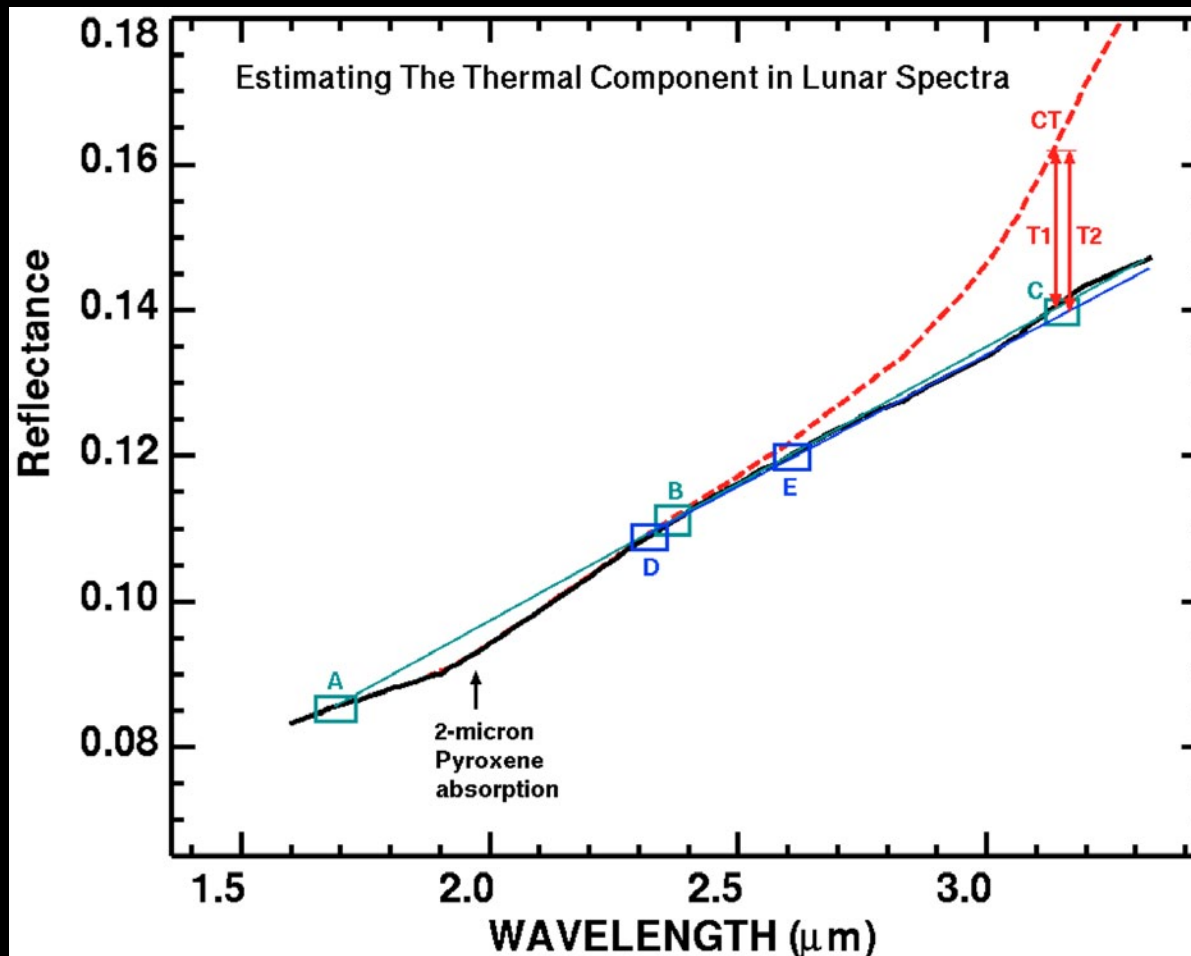
- Thermally emitted radiation is apparent at longer M³ wavelengths for warm surfaces
- Affects long wavelength spectral character
- Team has devised an approach to remove “excess” thermal emission component (see Clark et al., 2011 JGR)

Clark et al., 2011





Thermal Removal



- Project to C from A and B; remove thermal component (Planck function) T1
- Use T1-corrected spectrum, project to C from D and E, remove thermal component T2
- Third iteration (C from D and E) if derived temperatures bet. steps 1 and 2 vary by >2 K.
- Thermal emission NOT removed where no temperature derived (where no excess thermal component is detected).

Clark et al., 2011





Photometric correction

- Goal of photometric correction: normalize the reflectance to standard geometry: $i=30$, $e=0$, $a=30$
- $L2_{s4}(\lambda) = L2_{s3}(\lambda) * \{ X_{L_norm}(i_topo, e_topo, \alpha) * F_{alpha_norm}(\alpha, \lambda) \}$
 - Where XL is the limb darkening. It can be modeled by lunar-lambert (Clementine mission) or Lommel-Seeliger (LROC). We are using Lommel-Seeliger.
 - We use the topography derived from LOLA
 - And the $f(\alpha)$ is determined from the data itself





Photometric correction

- Data used to define the $F(\alpha)$
 - OP2C, representing ~ 1 full coverage of the Moon
 - Data have been thermally corrected (data subsetting by pixels where a temperature was derived in the previous step).
 - For data higher than 75 degrees latitude, we use of all pixels because thermal emission is \sim nonexistent.
 - We separate highland and mare using empirical model. The model use the reflectance at 750nm and the slope between 750 and 950 nm
 - We obtain $>100,000$ spectra
 - We cover phase angle from 0 to 100 degrees
- **Than we fit with a polynomial function** (*of order XX?*)

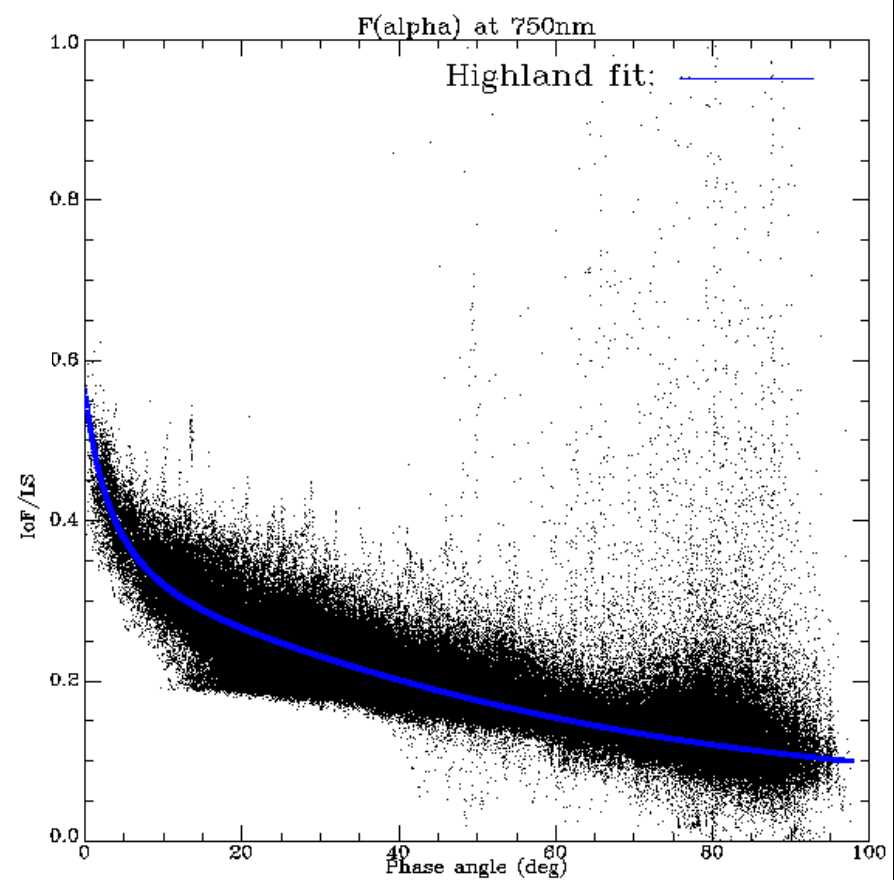
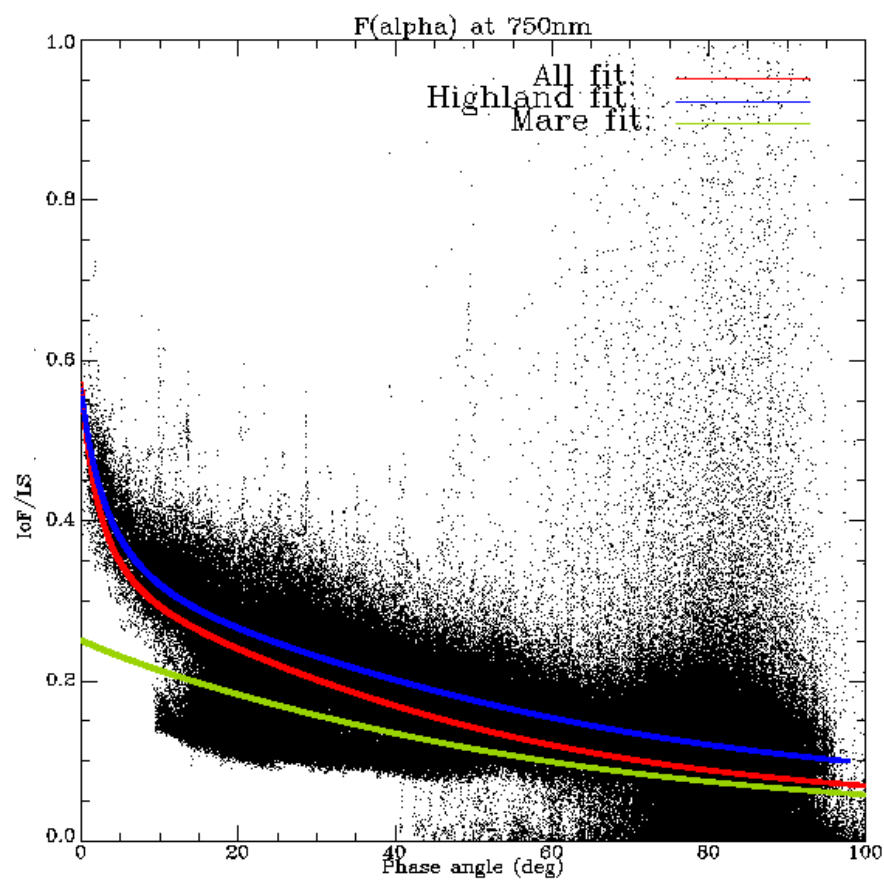




Photometric correction

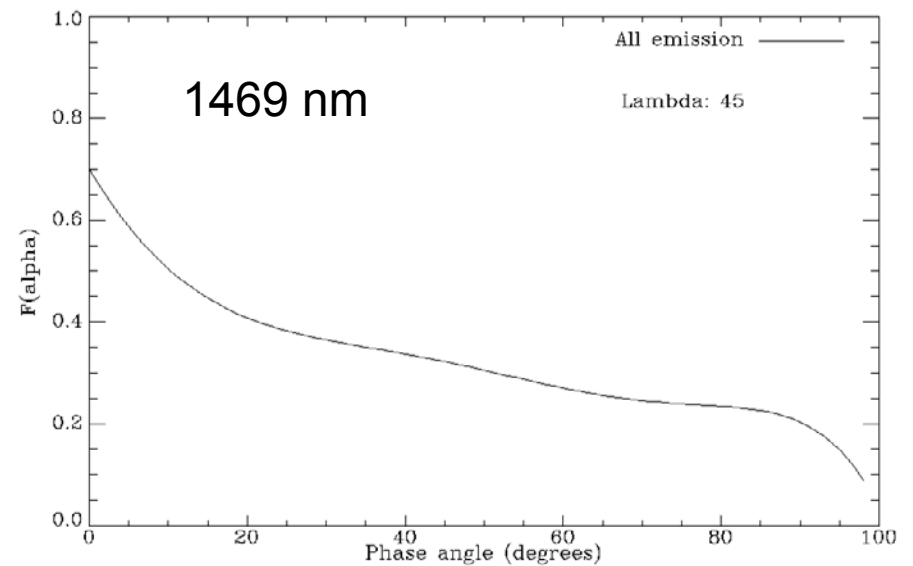
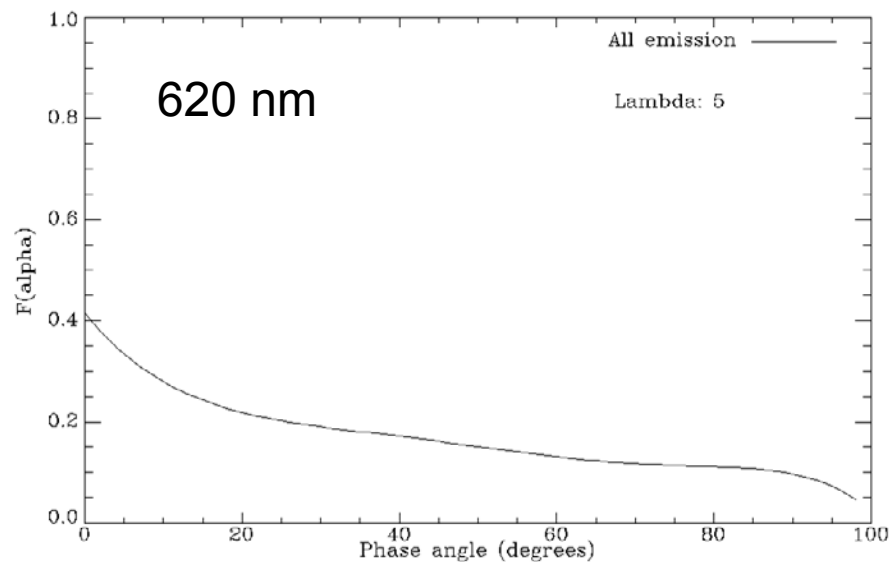
Mare & Highland

Highland only

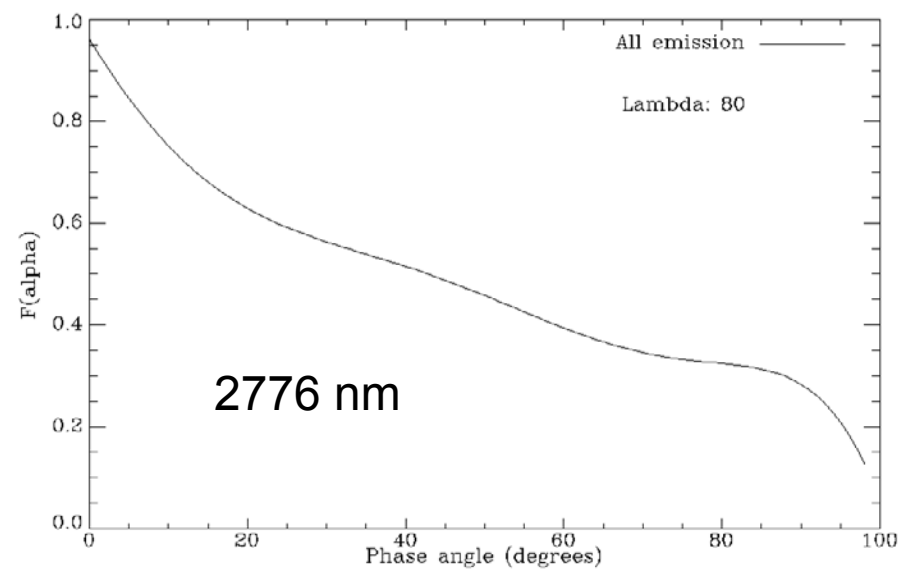




Photometric correction

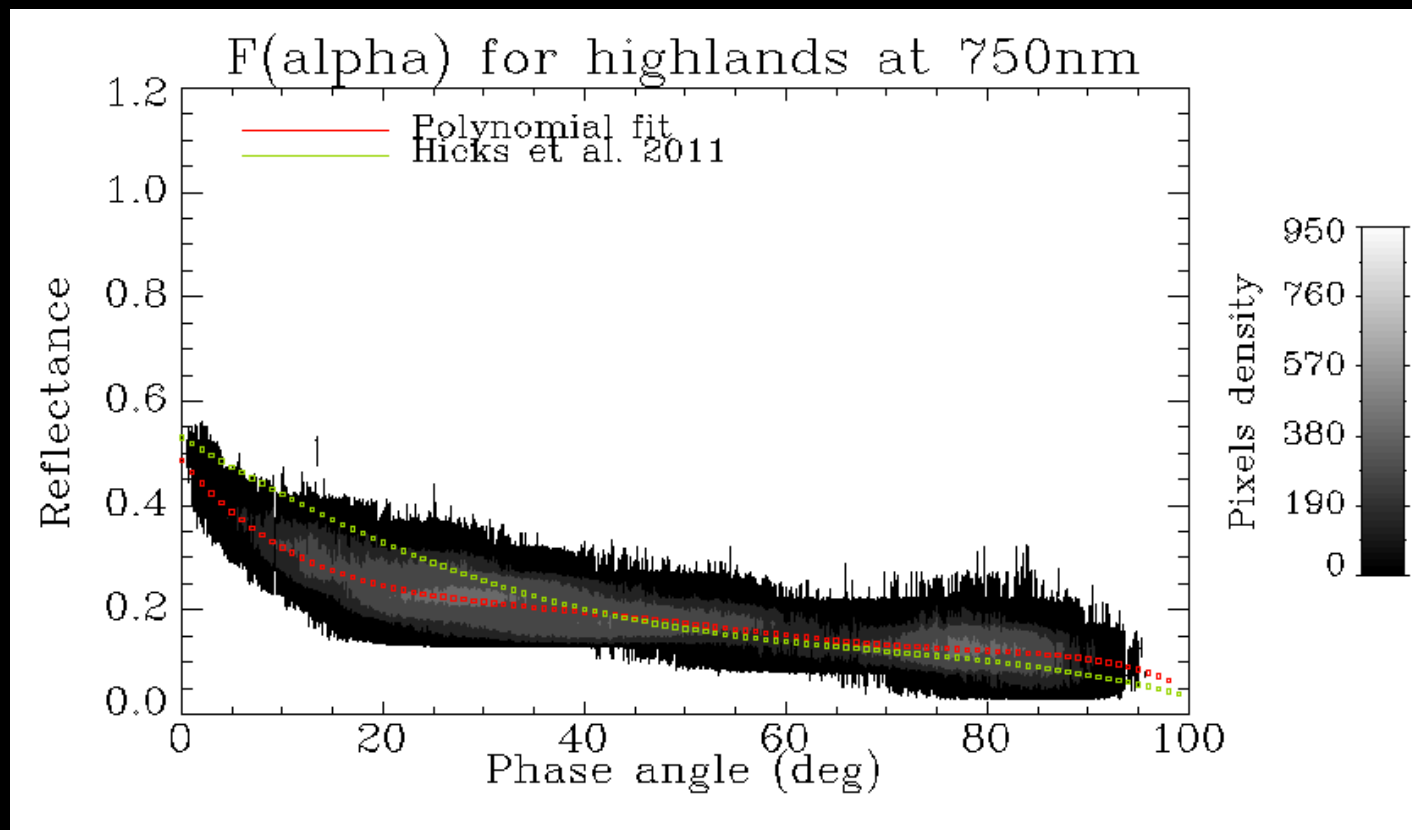


Highland fit for different wavelengths





Photometric correction

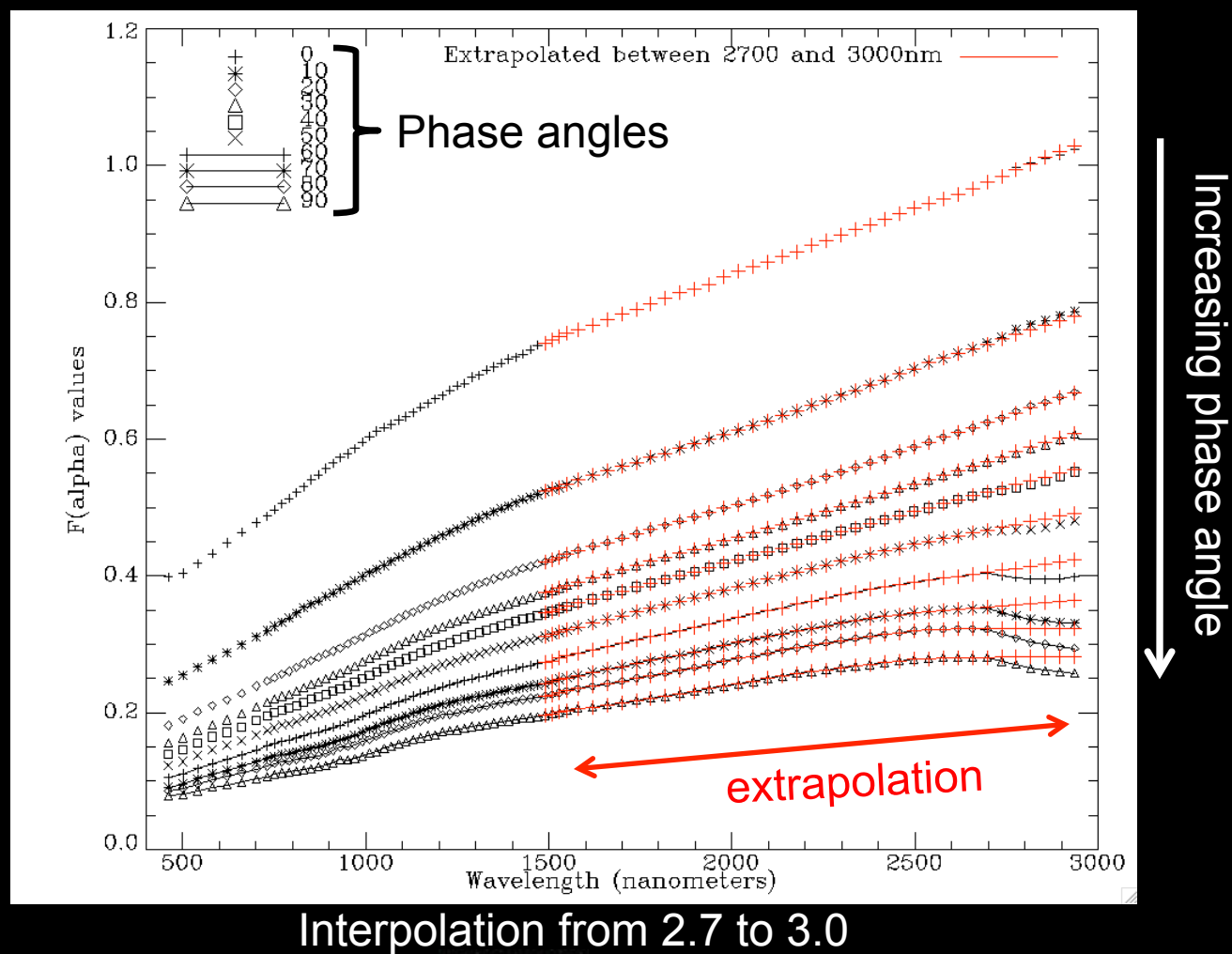


Comparison with previous model



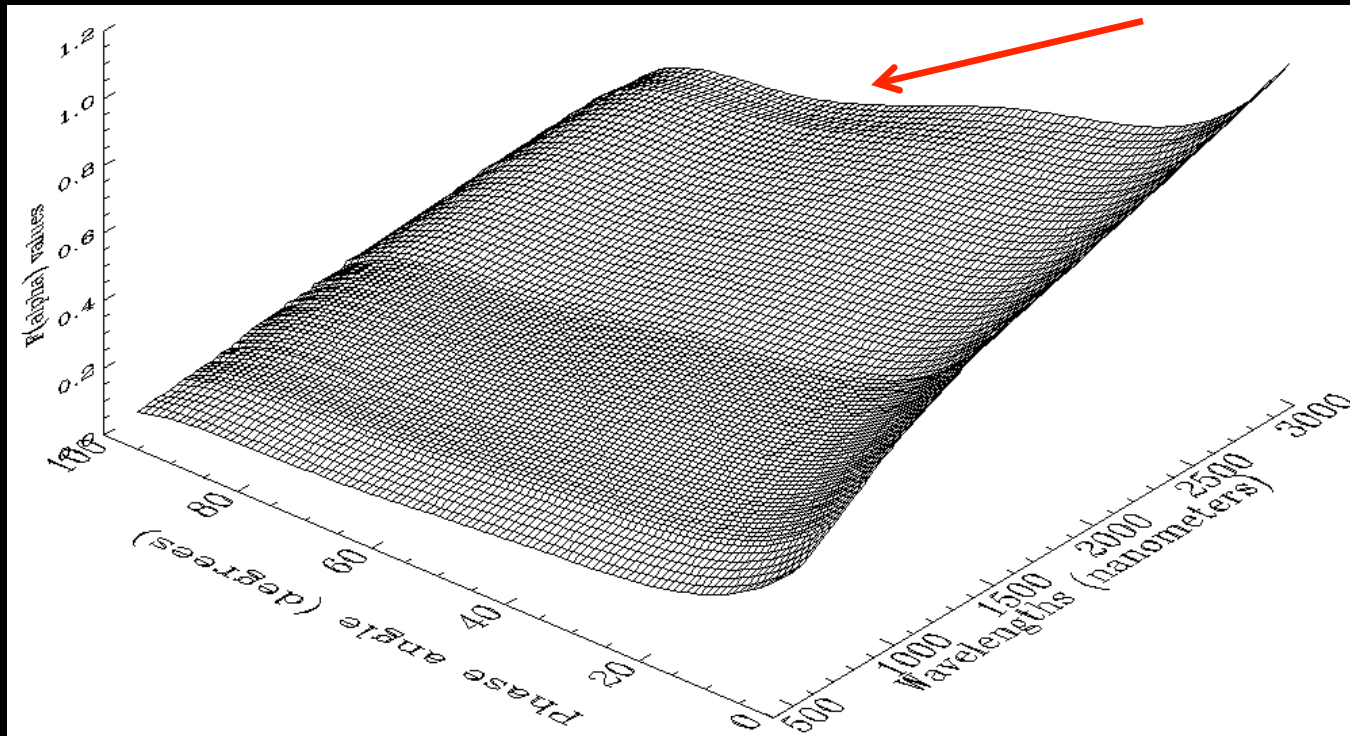


Photometric correction





Photometric correction

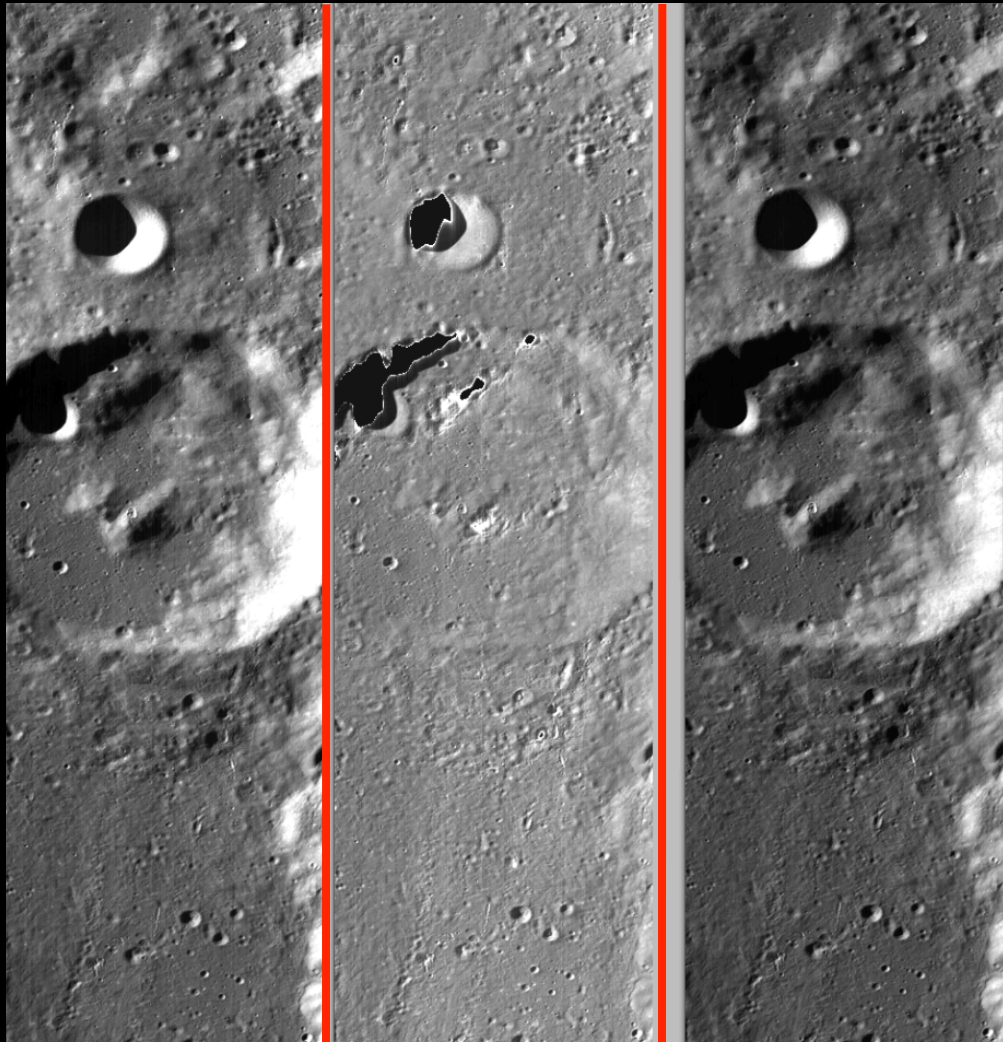


3D view of the derived $F(\alpha)$ function



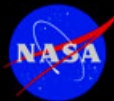


Photometric correction



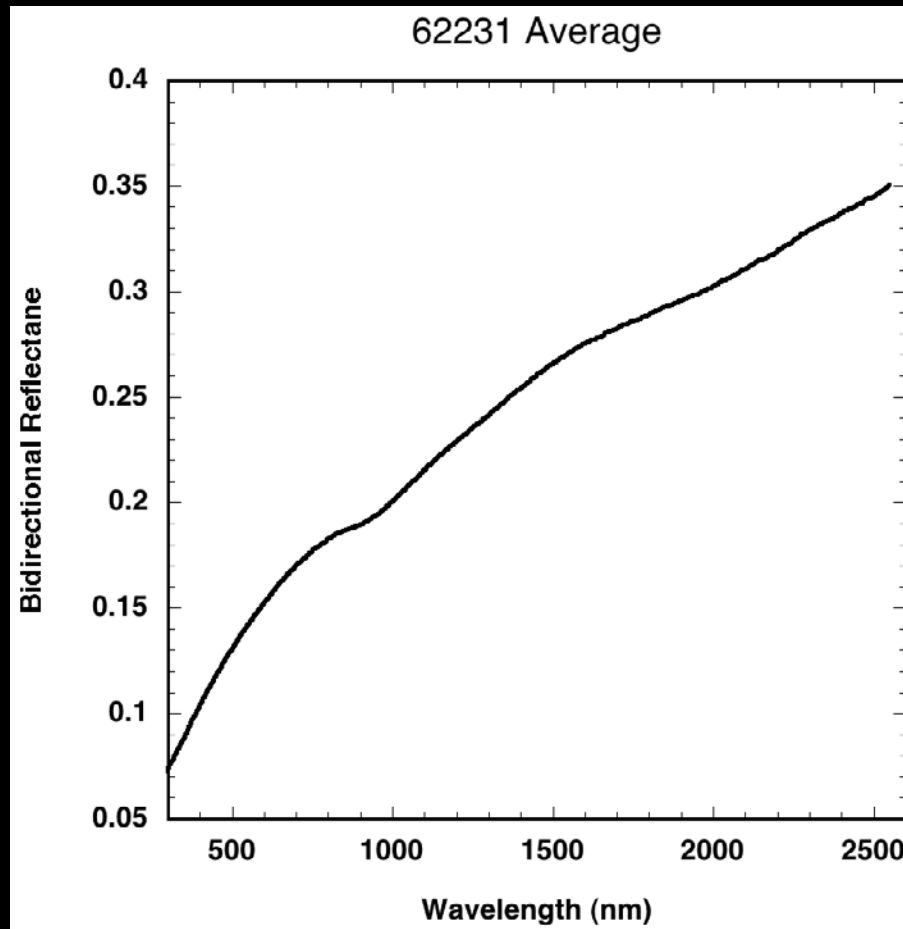
From left to right:
Reflectance
Reflectance + Photometry (topo)
Reflectance + Photometry (sphere)

Using Photometry with i,e,a from topo,
The topography itself disappears.





Ground truth correction

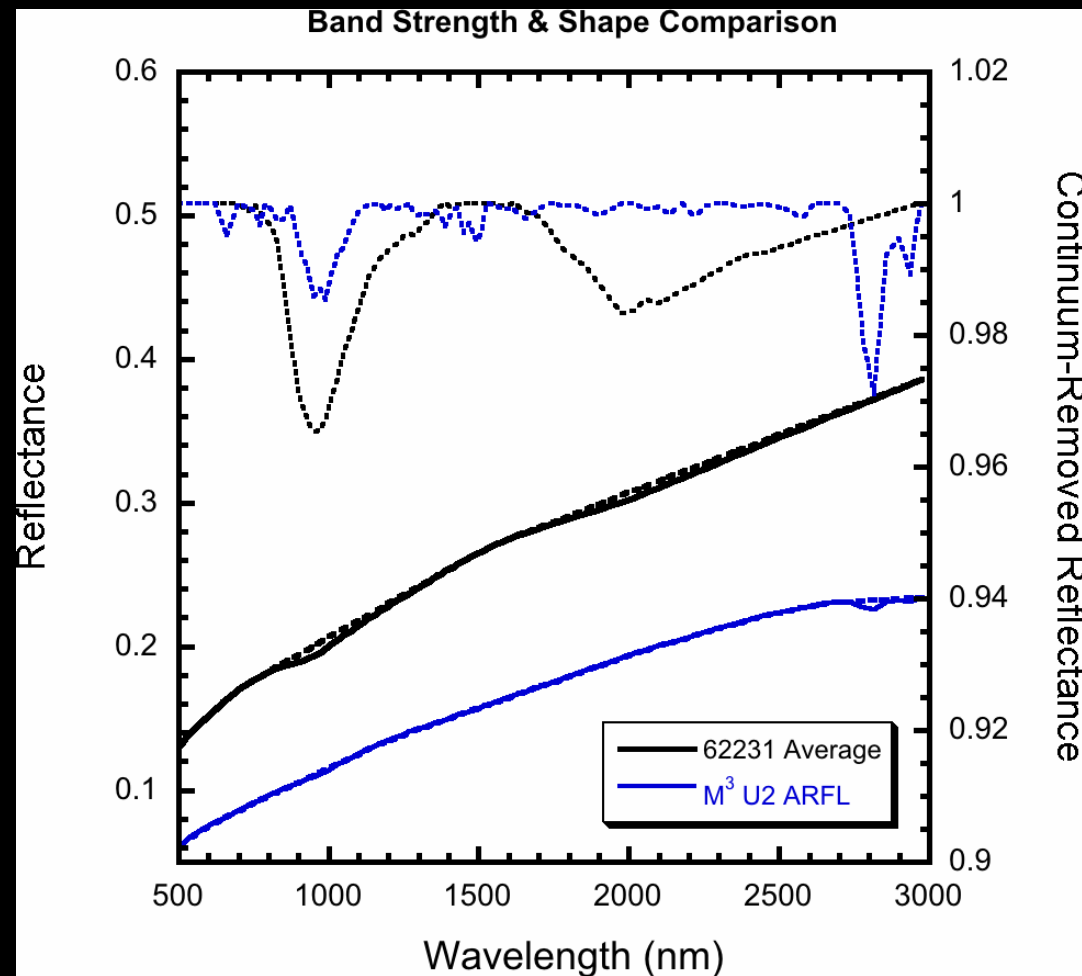


- Motivation for GT Correction: Spectral properties of mature lunar soils are well-understood from laboratory investigations.
- Ground truth correction will correct spectral character (absorption properties) for known regions and known spectral properties of mature soil.
- Ground truth correction will NOT change:
 - Absolute albedo
 - Continuum Slope





Ground truth correction



Approach

- Average 62231 soil spectrum is the basis of the correction
- Convex hull continuum removal (both M³ and lab)
- Ground truth is the final step in L2 correction steps and is reversible (correction factor to be stored in CALIB directory)





Summary of M^3 L2 data

- Steps in L2 production:
 - Divide by solar irradiance
 - Statistical polishing
 - Removal of thermal emission component
 - Photometric correction
 - Ground truth correction
- Level 2 delivery is imminent (late 2011)





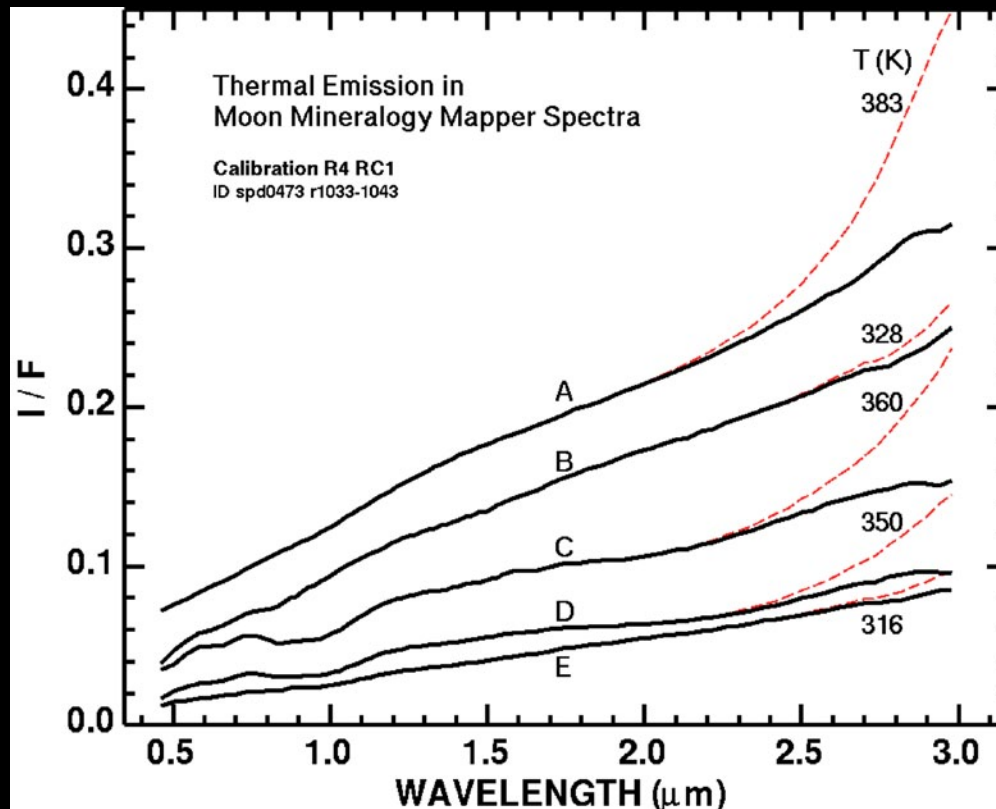
Words of caution regarding M3 dataset (**U2 Calibration**)

****U2 Calibration is the version included in
the Sept. 2011 Level 1 and late 2011
PDS data releases****





Thermal emission at long wavelengths (L1b only)



Clark et al., JGR 2011

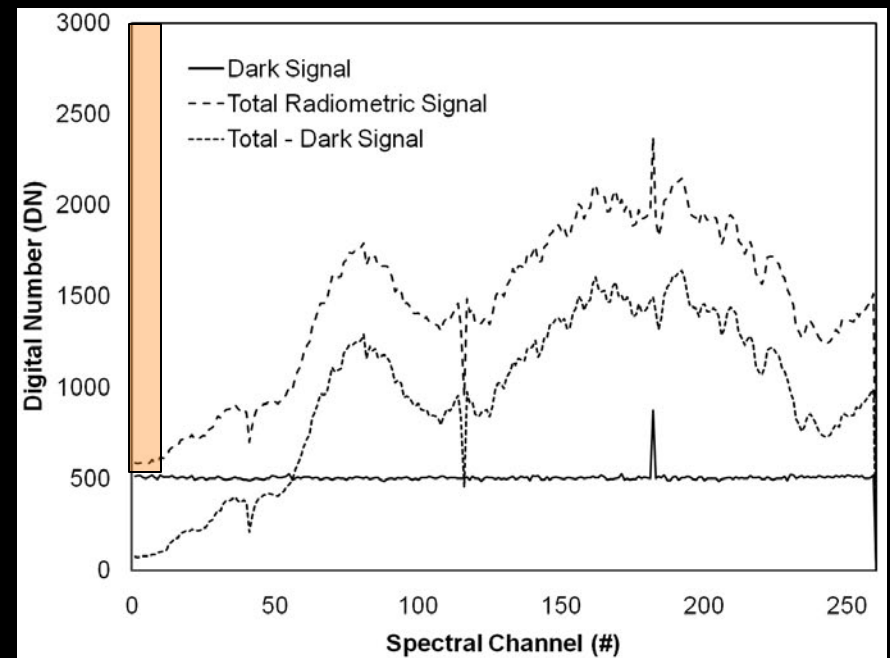
- M3 data contain a component of emitted thermal (black body) radiation.
- More extreme for warm/hot surfaces; more notable at long wavelengths
- Removal of thermal emission is discussed by Clark et al. (2011)





Low signal levels at short wavelengths

- The shortest wavelengths have the lowest overall signal. Given the unfortunate low lighting conditions for much of M³ data, these channels may not be far above the dark (offset) signal, which can contribute to a range of adverse effects on M3 data.
- These wavelengths thus often contain spurious effects and should **NOT** be used in ratio images or quantitative analyses.
- *L2 data from U2 data will be delivered with unreliable channels set to zero. [est. below 620 nm] (but will still contain 85 spectral bands).*
 - Caution should be exercised with U2 L1B data when converting to reflectance (L1B PDS archive does not have unreliable bands set to 0!).



Green et al. 2011, JGR





Working with L1B (radiance) data and creation of “Apparent Reflectance”





Converting Radiance to Apparent Reflectance

- If working with L1b (radiance) data, apparent reflectance (ARFL) can be derived in a straightforward manner:

$$IoF = \frac{I\pi d^2}{F}$$

- Where:
 - I = radiance in W/m²/Sr/μm
 - F = solar flux (solar spectrum) in W/m²/μm
 - d = Moon-Sun distance in AU

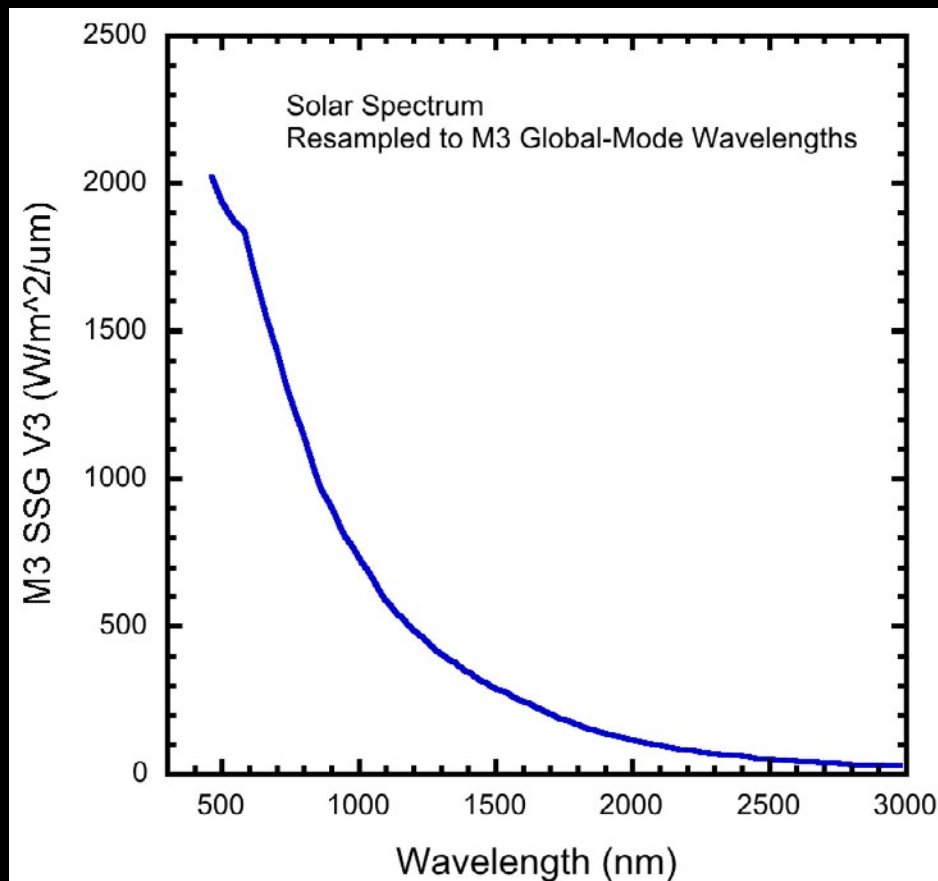




Download M3 Solar Spectrum

http://m3.jpl.nasa.gov/docs/solar_spec_global85.txt

http://m3.jpl.nasa.gov/docs/solar_spec_target256.txt



- MODTRAN-based
(See Green et al., 2011)
- Global and target resolution version can be downloaded in ASCII format from the above links
- See <http://m3.jpl.nasa.gov/m3data.html> for more





Download M3 Solar Spectrum

```
http://m3.jpl.nasa...spec_global85.  
ENVI ASCII Plot File [Mon Nov 22 17:44:36 2010]  
Column 1: Wavelength(nm)  
Column 2: M3 SSG V3 (W/m^2/um) ~~1  
460.989990 2022.662109  
500.920013 1934.504639  
540.840027 1875.621826  
580.765015 1833.137451  
620.689941 1689.644409  
660.609985 1550.267334  
700.537537 1428.238281  
730.479980 1324.721680  
750.440002 1271.074707  
770.400024 1216.917114  
790.364990 1162.946045  
810.330017 1107.837036  
830.290039 1053.718018  
850.250000 985.262878  
870.209961 946.577942  
890.174988 920.729126  
910.140015 879.042053  
930.099976 838.584351
```

- File is tab-delimited ASCII text
- 3 lines of header information to be skipped when importing





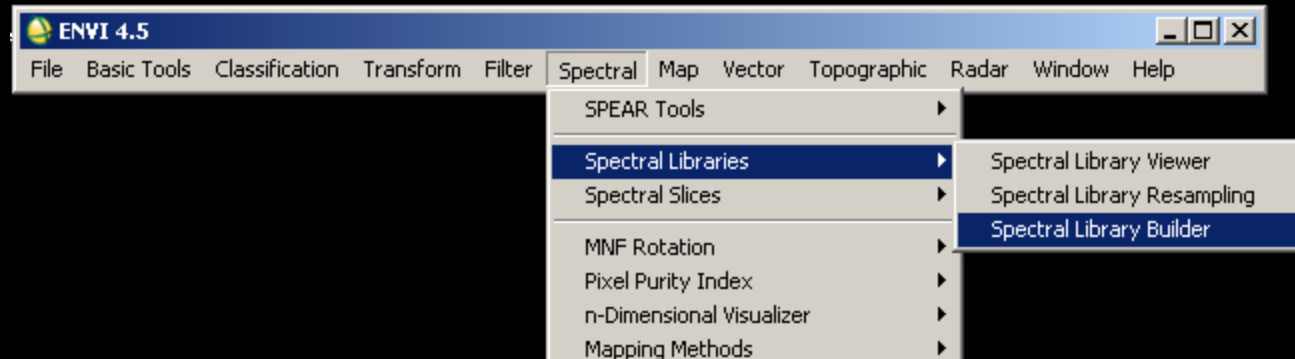
Steps to convert radiance to I/F in ENVI



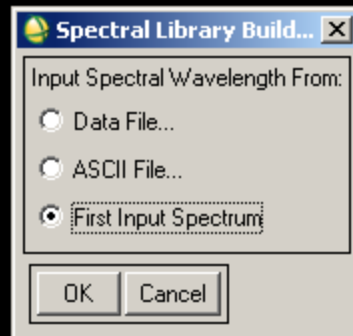


Step 1: Import M3 Spectral Library

- Step 1:



- Step 2:



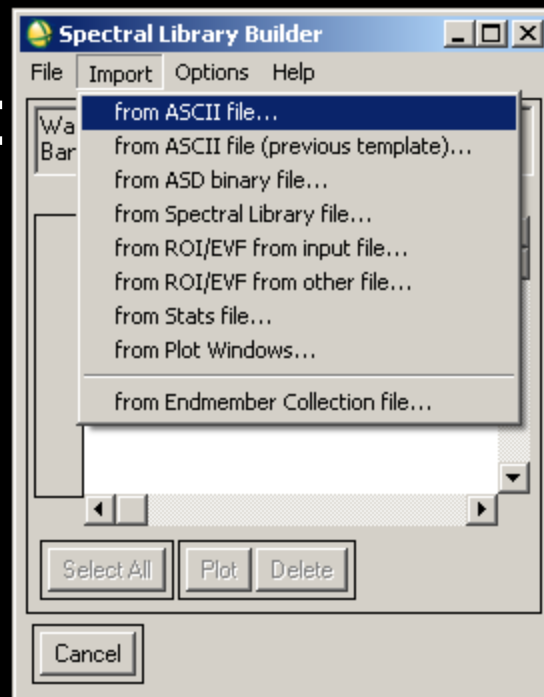
(Can also choose “ASCII File....” here but that has more steps)



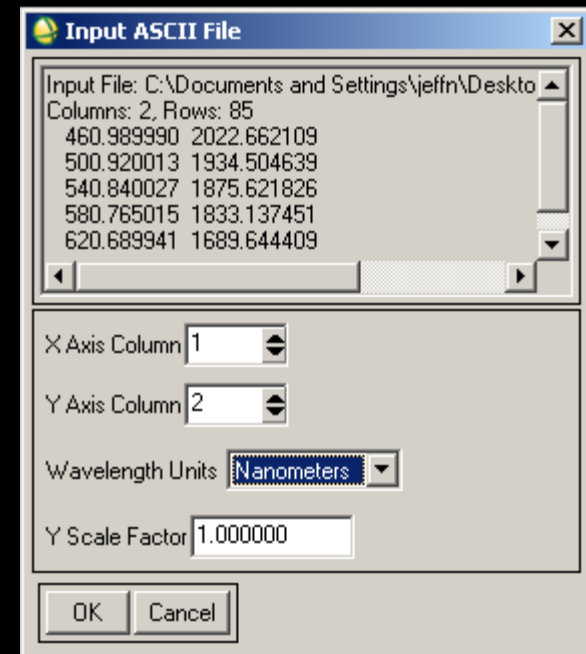


Step 1: Import M3 Spectral Library

Step 3:



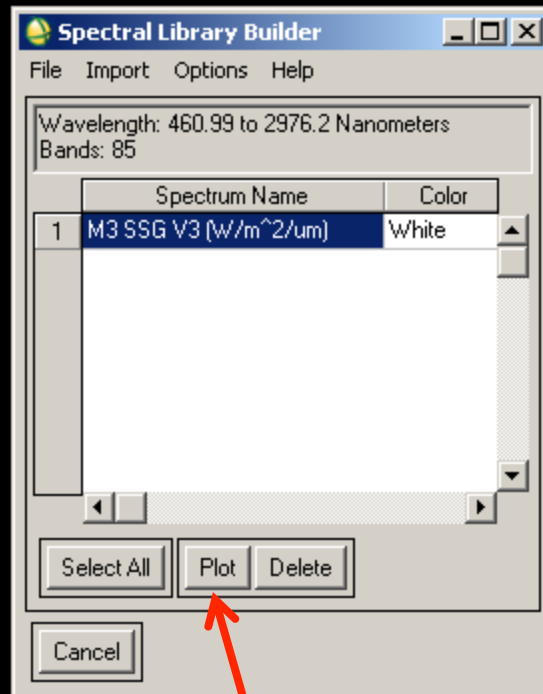
Step 4:





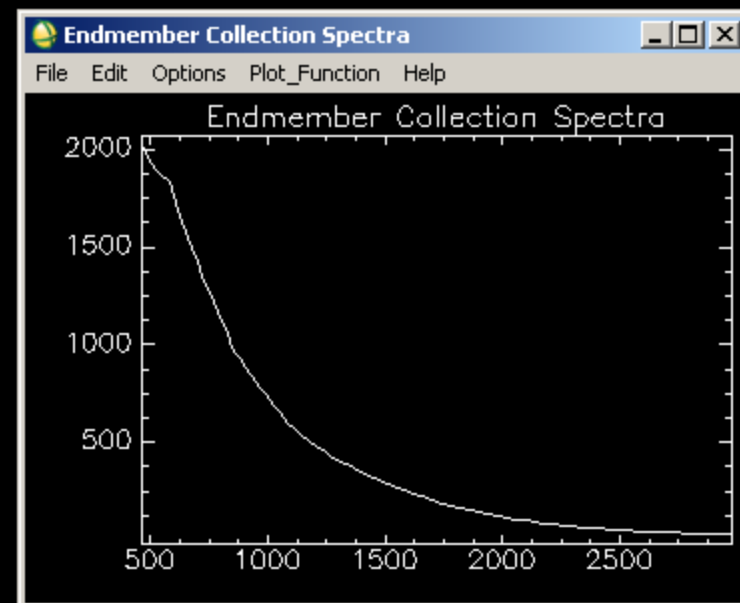
Step 1: Import M3 Spectral Library

Step 3:



Click Plot

Done!



(Can save file as spectral library from File menu)





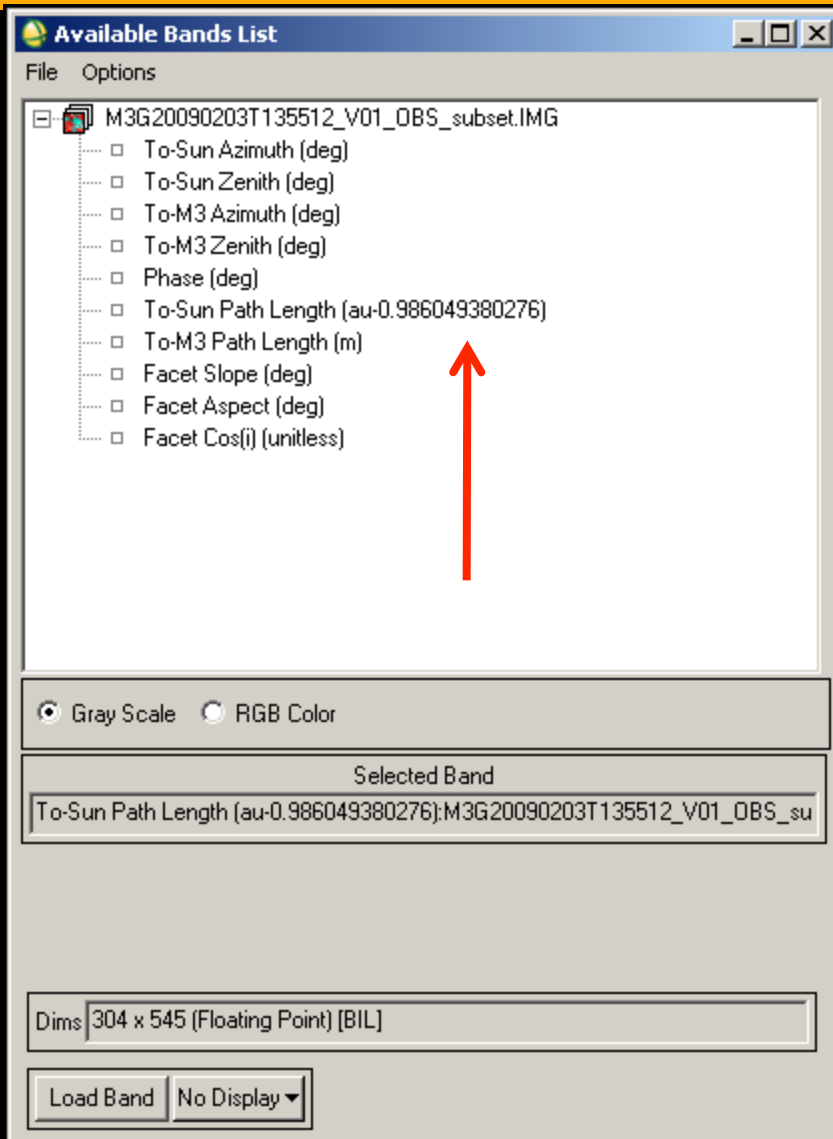
Step 2: Open Files

- Open radiance (RDN) file in ENVI:
 - File > Open Image File
- Open observations (OBS) file also
 - This step can be skipped if you want to use 1.0 AU for the Moon-Sun distance (~2% error)
- Open and plot the M3 solar spectrum if you have not already





Step 3: Get the Moon-Sun Distance

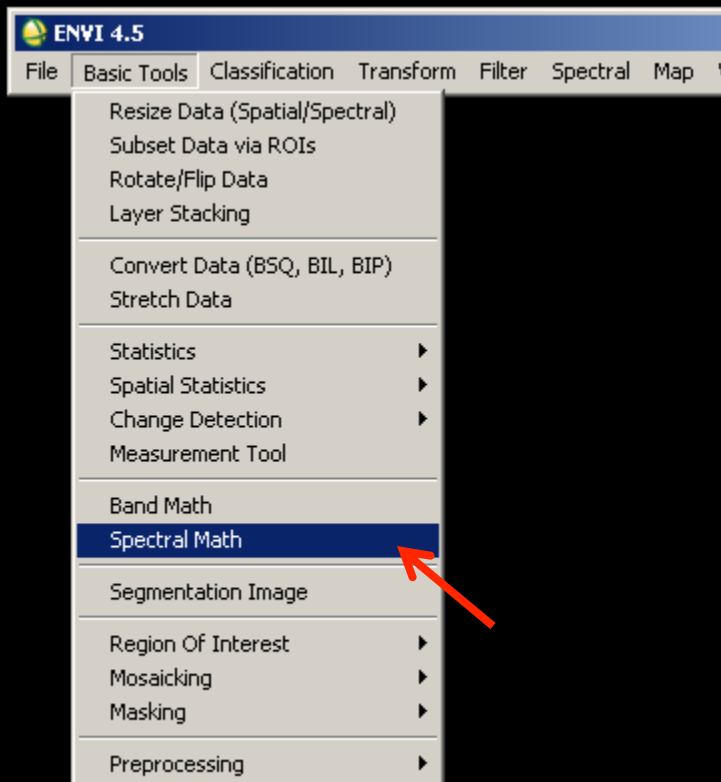


- Get mean distance from list of band names of the OBS file
- Could use per-pixel values in the To-Sun Path Length Band (band math)





Step 4: Call Spectral Math

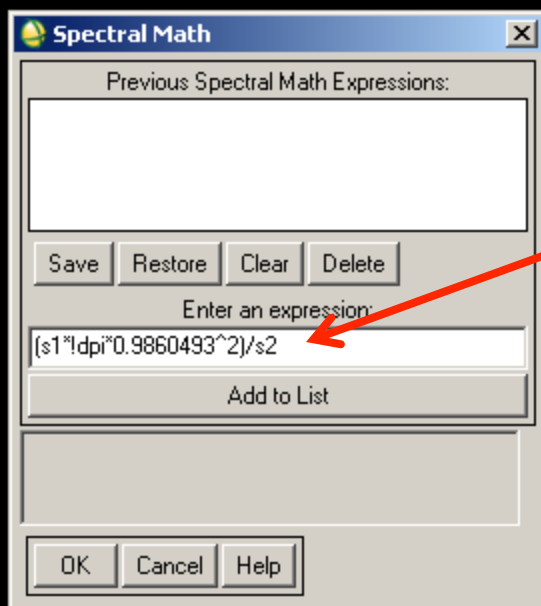


- Select Spectral Math under Basic Tools menu (also under Spectral menu)





Step 5: Enter the expression



- Expression is:
$$\text{float}((s1 * !dpi * 0.9860493^2) / s2)$$

Radiance

Double
precision π

Moon-Sun
distance
squared;
variable
per file...

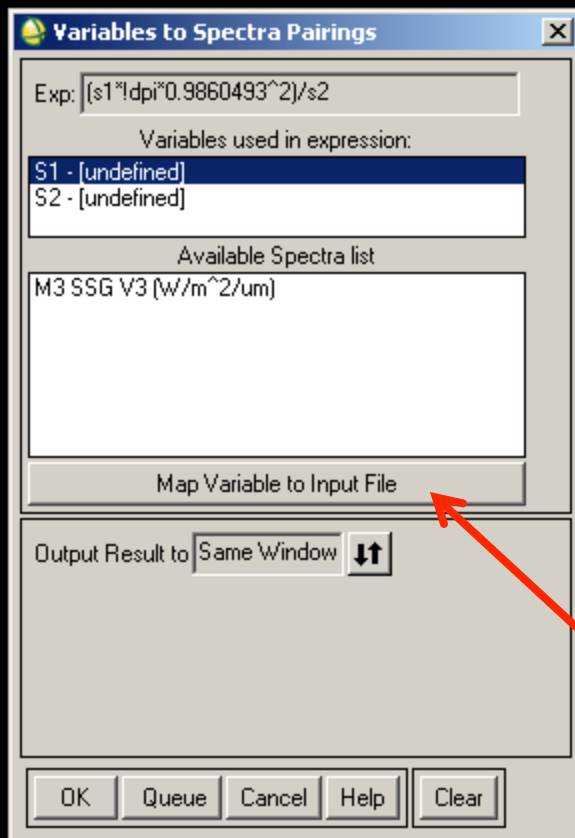
Solar
Spectrum



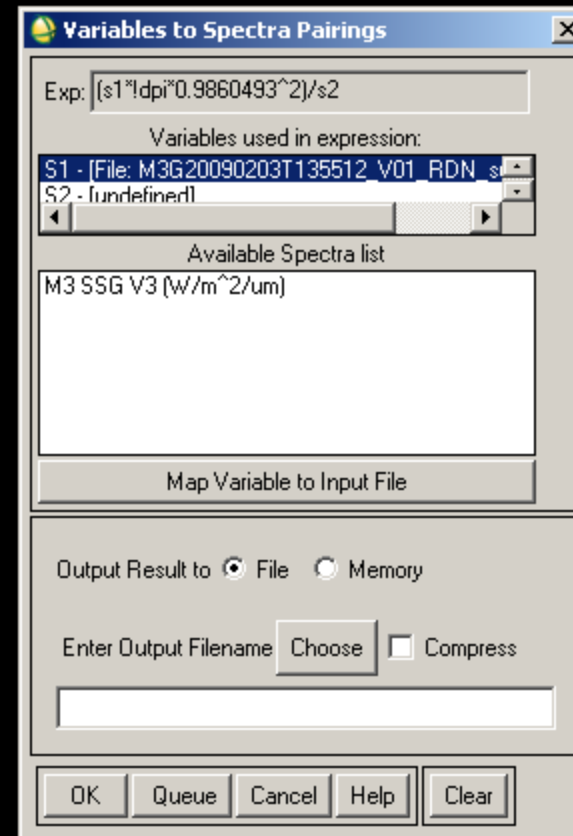


Step 6: Define s1

Click “Map Variable to Input File” and select your radiance (RDN) file

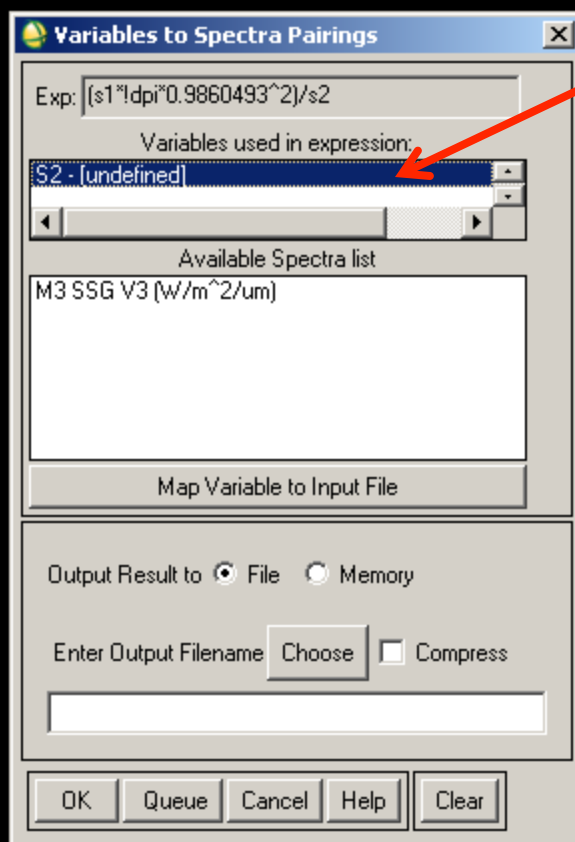


Should end up with this:



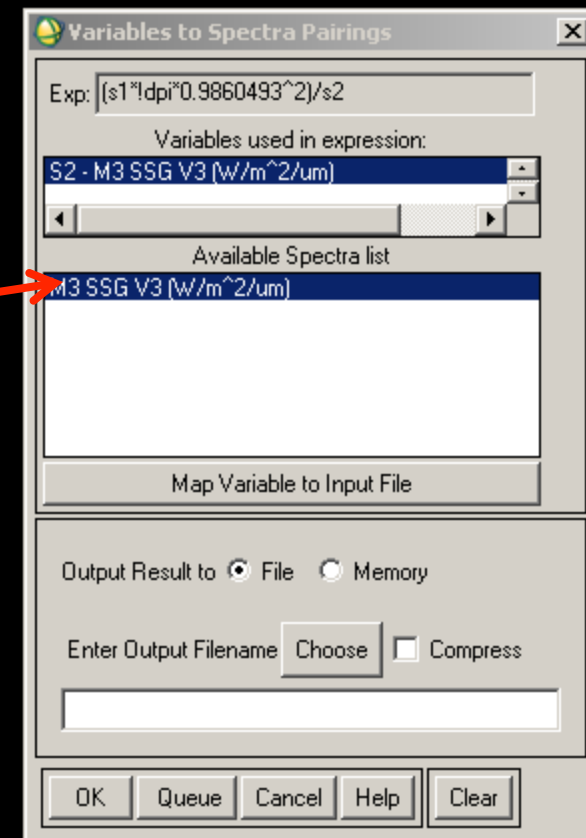


Step 7: Define s2



First Click

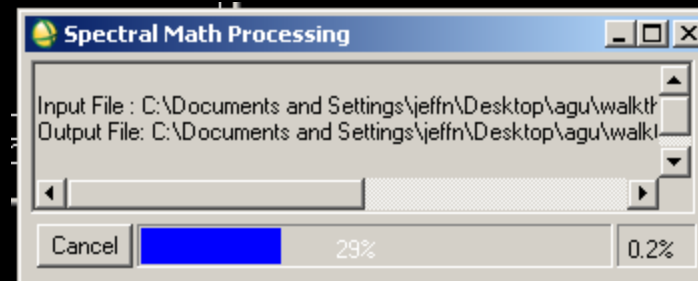
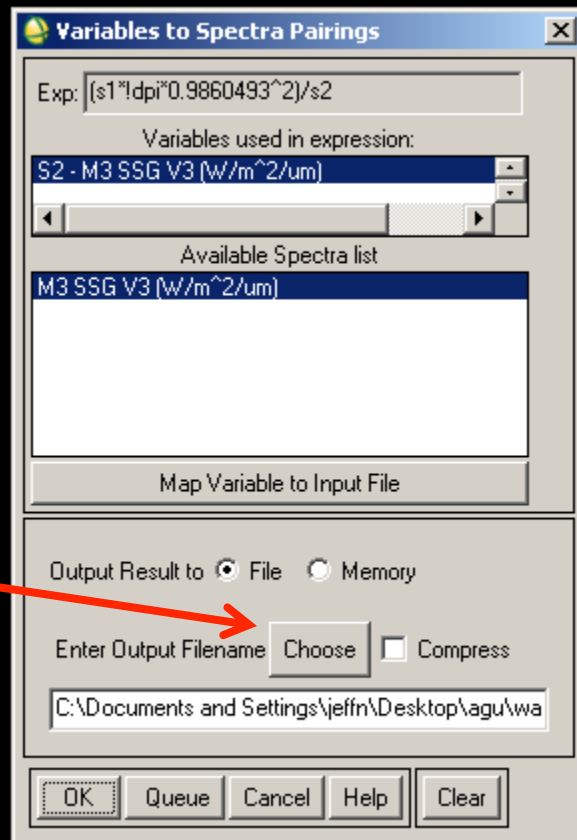
Second Click





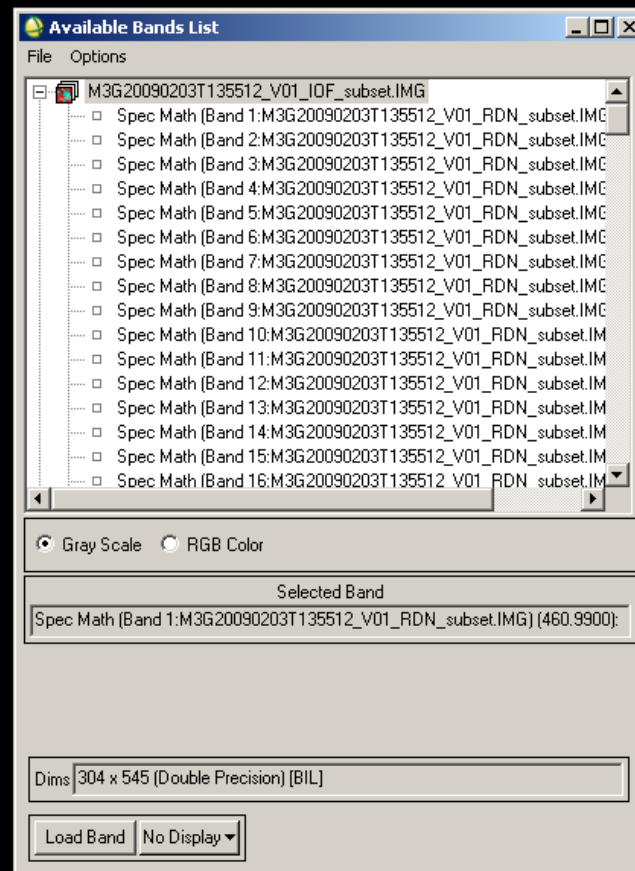
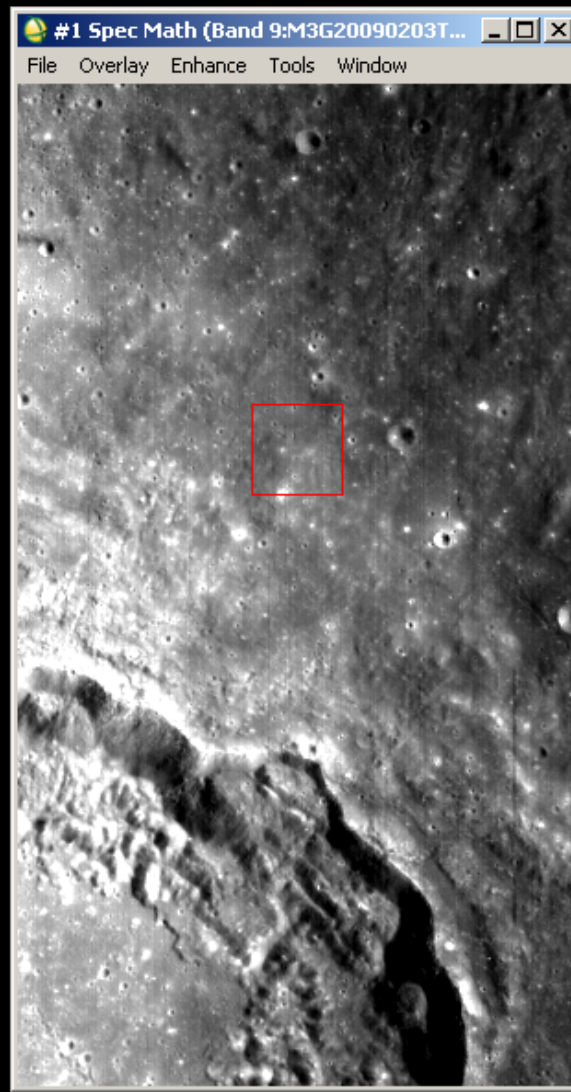
Step 8: Choose Output File

- Then click “OK” and ENVI goes to work...





Last Step: Enjoy!





Check your work!

- Example radiance, observations, and I/F file posted to M3 website so that you can make sure you get the same answer we do:
- <http://m3.jpl.nasa.gov/m3data.html>
- Filename:
M3_TestSubsetCube_M3G20090203T135512_R4.zip
- Note: radiance cube is in older R4 radiance calibration, not U2 as delivered 9/30/11

